

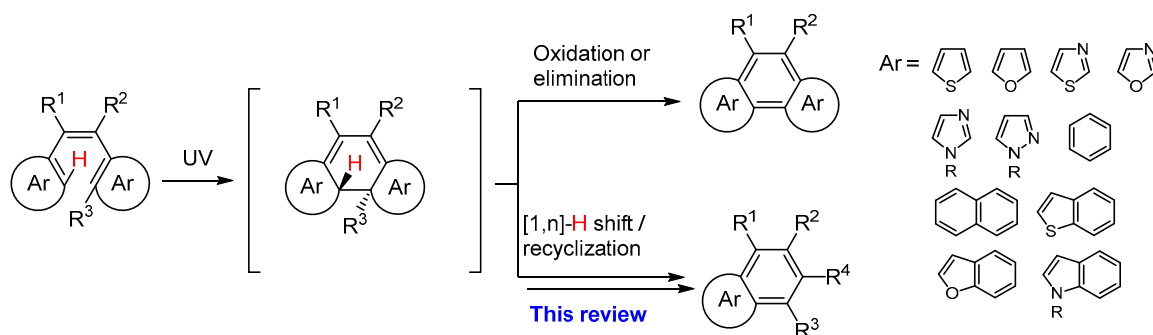
Photoinduced rearrangements of diarylethenes

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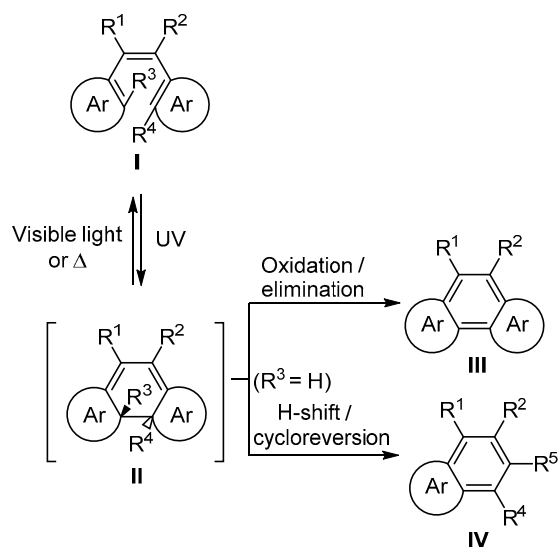


The photocyclization of stilbenes and their heterocyclic analogs has gained major importance in the synthesis of poly(hetero)aromatic compounds. This reaction generally leads to the formation of phenanthrene derivatives or their isosteric heterocyclic analogs. Over the last 15 years, examples of a new type of diarylethene reactions have been published, leading to bicyclic, instead of tricyclic aromatic products. These reactions are based on a sigmatropic hydrogen shift followed by the opening of one aromatic ring, and these transformations are applicable to the preparation of various aromatic compounds. Similar reactions are also highly relevant to the photostability of photochromic diarylethenes and terarylenes, thus the study of these compounds is important for the development of photo-controlled advanced materials and devices. In this review we provide the first analysis of scientific literature on this new type of diarylethene photoreactions.

Keywords: diarylethenes, terarylenes, electrocyclization, hexatriene system, photochemical synthesis, photorearrangement.

In recent years, synthetic photochemistry, i.e., preparation of organic molecules using light has been rapidly developing.^{1–5} The progress in photochemical synthesis is largely provided by the search for structural moieties able to participate in specific organic reactions. One of such motifs, which is reactive in a wide range of various transformations, is the hexa-1,3,5-triene moiety.⁶ Among the types of compounds containing hexa-1,3,5-triene system, stilbenes (1,2-diphenylethenes) and, more generally, 1,2-diaryl(hetaryl)ethenes are the most studied (compounds I, Scheme 1). The cyclization of hexatriene system in 1,2-diaryl(hetaryl)ethenes (further referred to as diarylethenes for simplicity) involves two double bonds from each aryl moiety and the central vinyl group, which links these parts of the molecule. Diarylethenes can be formally divided in two types: diarylethenes with cyclic or acyclic central ethene moiety (ethene "bridge"). In the case when the ethene "bridge" represents an aromatic ring, the compounds are known as terarylenes. The inclusion of the central ethene group in cyclic system prevents the

Scheme 1



possibility of such processes as *E/Z* isomerization and (2+2) cycloaddition.

Diarylethenes undergo 6π -electron cyclization upon UV irradiation, forming metastable cyclohexadiene derivatives **II** (Scheme 1). The most common processes involving these reactive intermediates are oxidation or elimination reactions that produce related synthetic results.^{7–9} As first reported in 1950, stilbene is converted to phenanthrene by UV irradiation.¹⁰ This reaction became a prototype for a classic method of organic synthesis, actively used for the preparation of tricyclic polyaromatic compounds **III**, derivatives of phenanthrene and its isosteric heterocyclic analogs.

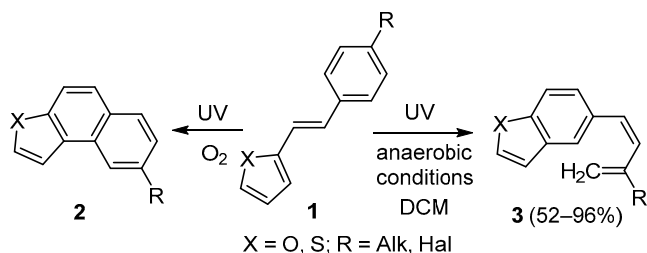
Besides the applications in the field of organic synthesis, cyclization of diarylethenes has found use in the design of photochromic compounds.^{11,12} In this case, the photo-induced form **II**, as a rule, is sufficiently stable thermally and chemically, but can be converted to form **I** by visible light (Scheme 1). The photochromic properties of diarylethenes, primarily their heterocyclic analogs, have been studied fairly extensively over the previous 25 years, including the thermal stability of photoinduced form, quantum yields of the direct cyclization reaction and the reverse recyclization, fatigue resistance (cyclicality), and other physicochemical characteristics.^{13–16} It is highly important to establish the factors affecting the stability of form **II**, in order to develop practically useful photo-controlled devices and materials based on diarylethenes. For example, previous studies elucidated the reactions of formal 1,2-dyotropic rearrangement leading to isomers containing two six-membered fused heterocycles,^{17–20} irreversible cyclization at the β -position of thiophene,^{20,21} addition of oxygen,²¹ thermal decomposition of diarylethenes containing a thiophene-*S,S*-dioxide system,^{22–24} and elimination of suitable leaving groups from the photochemical reaction site.^{25,26}

A range of publications over the previous 15 years have described photoinduced cascade transformations of various diarylethenes and terarylenes, leading to the formation of bicyclic, instead of tricyclic aromatic products, due to opening of one of the aromatic rings (Scheme 1, compounds **IV**). The specific synthetic outcome and general mechanistic features of this reaction indicate that it belongs to a separate class of domino reactions (also known as cascade or tandem reactions),^{27,28} which have been actively developed in recent years. Detailed understanding of this type of transformations is very important for the design of highly stable photochromic diarylethenes. The aim of this review is to summarize data on similar transformations, with an emphasis on mechanistic and synthetic aspects of these reactions.

It was reported by Ho and coworkers in 1999 that 2-styrylfurans and styrylthiophenes **1**, which upon irradiation in the presence of oxidants (air oxygen or iodine) give the standard reaction products, phenanthrene analogs **2**, are unstable under inert atmosphere, and tend to undergo rearrangement to butadienyl-substituted benzofurans and benzothiophenes **3** (Scheme 2).²⁹ This result was contrary to the previous knowledge about the stability

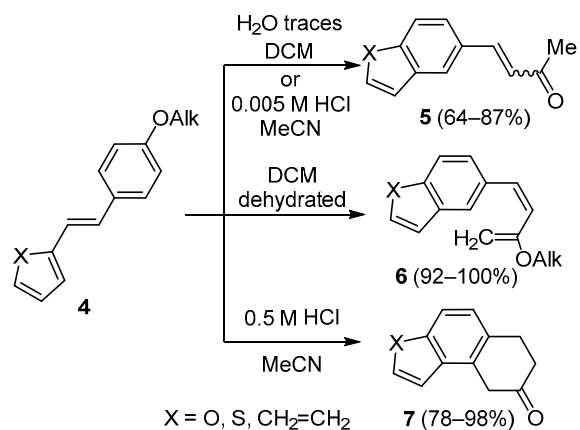
of photoinduced isomers of heterocyclic stilbene analogs under inert atmosphere.³⁰ This reaction of diarylethenes bearing alkyl and halogen substituents in the benzene ring gave relatively high yields (despite the incomplete conversion of a range of substrates), while the introduction of other substituents (nitro, dialkylamino, or cyano groups) resulted in a complete suppression of rearrangements.

Scheme 2



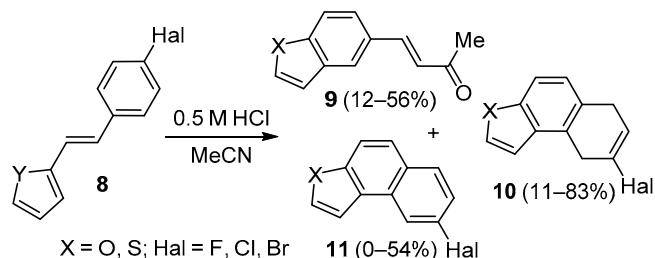
The next step in the development of this rearrangement as a synthetic tool was accomplished by introducing a methoxy group at position 4 of benzene ring (substrates **4**, Scheme 3). It should be noted that the authors demonstrated at this stage not only the reaction with "mixed" diarylethene **1** containing both furan and thiophene rings, but also used the more conventional diphenyl-substituted stilbenes. It was shown that the presence of moisture in the reaction solvent (dichloromethane) resulted in hydrolysis of the photo-induced intermediate, forming the vinyl ketone product **5**, while the absence of moisture led to the vinyl ether **6**.³¹ Analogous results were obtained by carrying out the reaction in the presence of hydrogen chloride (0.005 M).³² Finally, it was established that the concentration of acid has an important role in determining the reaction route: tricyclic products **7** are formed in more concentrated solutions.³³ The range of suitable substrates was further extended to 2-methoxy-substituted stilbenes, the behavior of which was largely similar to that of 4-methoxy derivatives.³⁴

Scheme 3



The irradiation of diarylethenes bearing a halogen atom instead of methoxy group in solutions with higher HCl concentration produced generally similar results, but the selectivity was lower.³⁵ Compounds **8** gave mixtures of three products, benzoheterocycles **9** (analogs of compounds **5** in the case of methoxy derivatives), tricyclic heterocycles **10** ("non-hydrolyzed" analogs of compounds **7**), and the oxidation products **11** (Scheme 4). The latter result was explained by authors as a result of redox transformation involving hydrogen chloride, probably *via* a radical process.

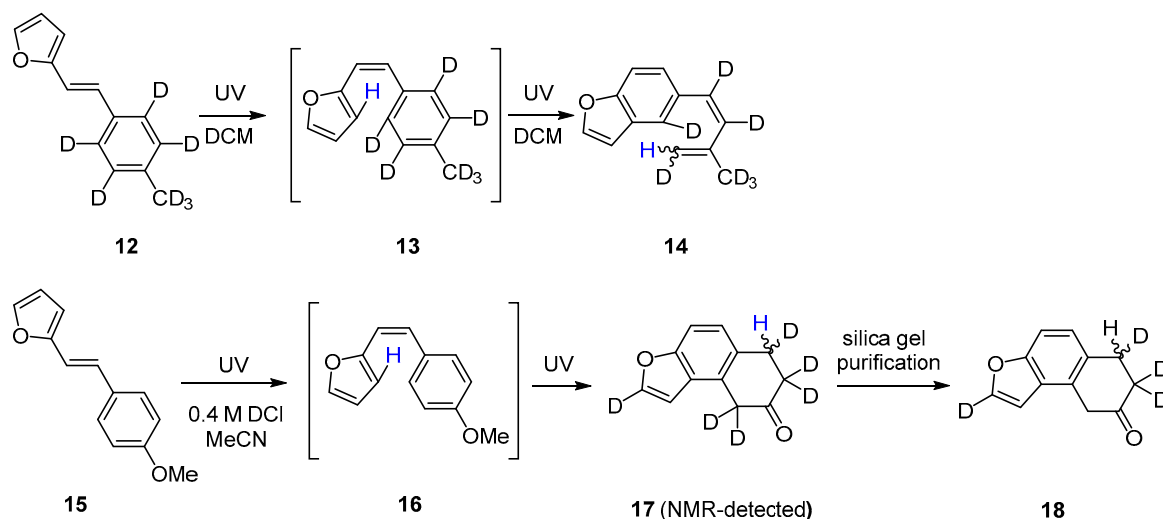
Scheme 4



Isotopic labeling experiments (Scheme 5) showed that in the first case there was a hydrogen atom migration from the furan ring of compound **12** to the terminal position of butadiene moiety in product **14**, providing formal evidence of [1,9]-sigmatropic shift.²⁹ Irradiation of diarylethene **15** in the presence of deuterated hydrochloric acid gave compound **17** according to NMR spectra. The isolation of this compound was associated with partial isotopic exchange, forming the product **18**.³² This result indirectly confirmed that the reaction occurred through stages of [1,9]- and [1,3]-sigmatropic shifts.

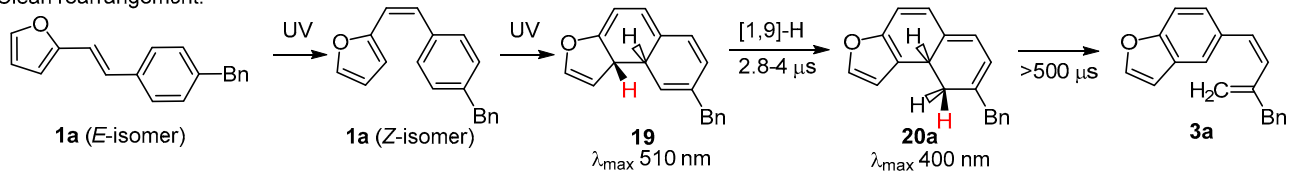
Further investigation of the reaction mechanism³⁶ using physical and chemical methods has completely confirmed these results (Scheme 6). The key intermediates of the reaction have been revealed by flash photolysis of diarylethene **1a**. The two-photon transformation of *E*-isomer of compound **1a** led to the intermediate **19**, which had its absorption maximum in the visible range. Further, it has been observed the rapid conversion of the latter to another intermediate due to a thermal [1,9]-sigmatropic shift. Undoubtedly, the restoration of aromaticity in furan ring

Scheme 5

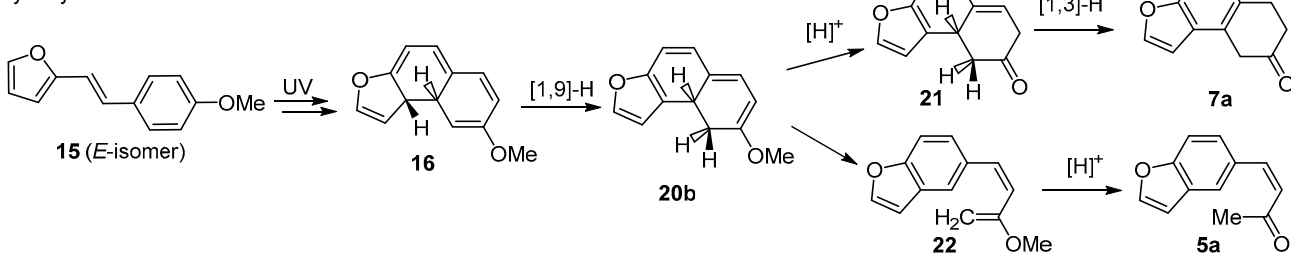


Scheme 6

Clean rearrangement:



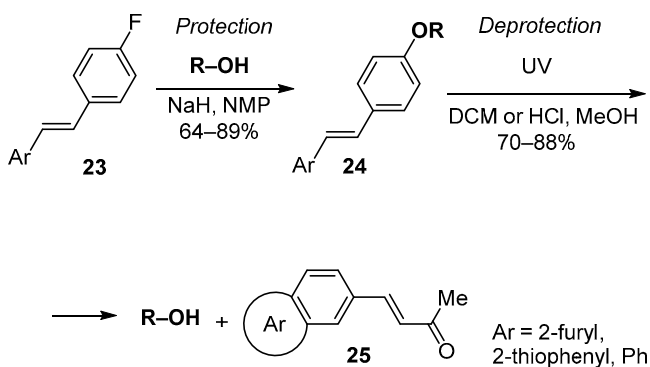
Hydrolysis variants:



played an important role in this key step. The last step is cyclohexadiene-hexatriene recyclization of intermediate **20a**. For diarylethenes with methoxy group, the stability of intermediate **20b** strongly depends on hydrogen chloride concentration in reaction solutions. At higher concentrations of hydrogen chloride (for the synthesis of compounds **7**), relatively fast hydrolysis of intermediate **20b** to compound **21**, followed by [1,3]-sigmatropic shift is observed. At lower concentration of hydrogen chloride, an alternative path is realized, namely, the intermediate **20b** prior to the hydrolysis undergoes cyclohexadiene-hexatriene recyclization, resulting in the bicyclic product **5a**.

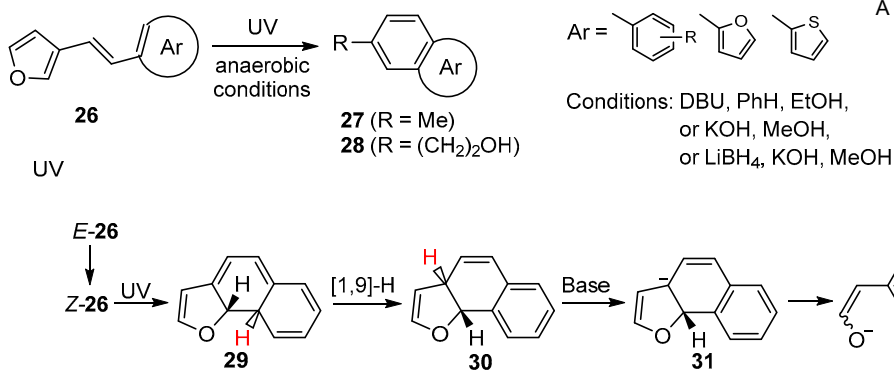
Besides the synthetic applications, acid-catalyzed rearrangements of 2-styrylfurans were used as a method for the introduction and selective photo-controlled removal of protective groups in primary alcohols.³⁷ The protection process of primary alcohol includes the stage of arylation with diarylethenes **23** in the presence of sodium hydride, producing the protected derivatives **24**, and the removal of protecting group by photorearrangements under acidic conditions, providing compounds **25** (Scheme 7).

Scheme 7



The applications of this method for the synthesis of polyaromatic compounds were further developed as base-catalyzed reactions of 3-styrylfurans **26** and their analogs (Scheme 8).^{38,39} Depending on the reaction conditions, the predominant products were compounds **27** or **28** with methyl or 2-hydroxyethyl groups originating from the furan ring of the starting material. The reactions gave no

Scheme 8

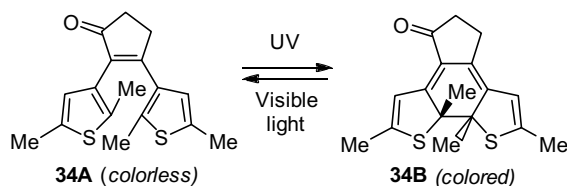


more than moderate yields in the majority of cases. The reaction mechanism was described by authors without referring to the concept of sigmatropic shifts, but the migration of hydrogen clearly took place. Taking into account the aforementioned data for other styrylfurans, this reaction probably also occurred by a mechanism involving [1,9]-sigmatropic shift during the conversion of compound **29** to compound **30** (Scheme 8).

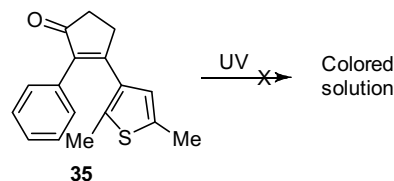
As indicated above, the photocyclization of hexatriene system has found applications in the design of bistable photoswitchable compounds. In the course of our study of photochromic diarylethenes of cyclopentenone ethene "bridge" series, we have observed an unusual pattern, where compounds based on 2,5-dimethylthiophene and benzene showed different activity (Scheme 9). While diarylethene **36A** with benzene ring at the third position of the "bridge" exhibited photochromism (even though the effect was limited to a few cycles, in contrast to the typical photochrome **34A**), its isomer **35** did not generate the colored form upon irradiation.⁴⁰

Scheme 9

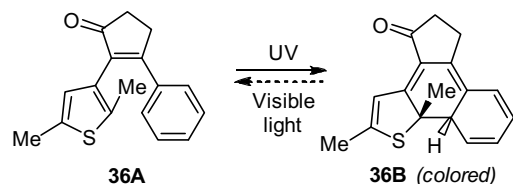
Typical photochromic diarylethene



Non-photochromic isomer



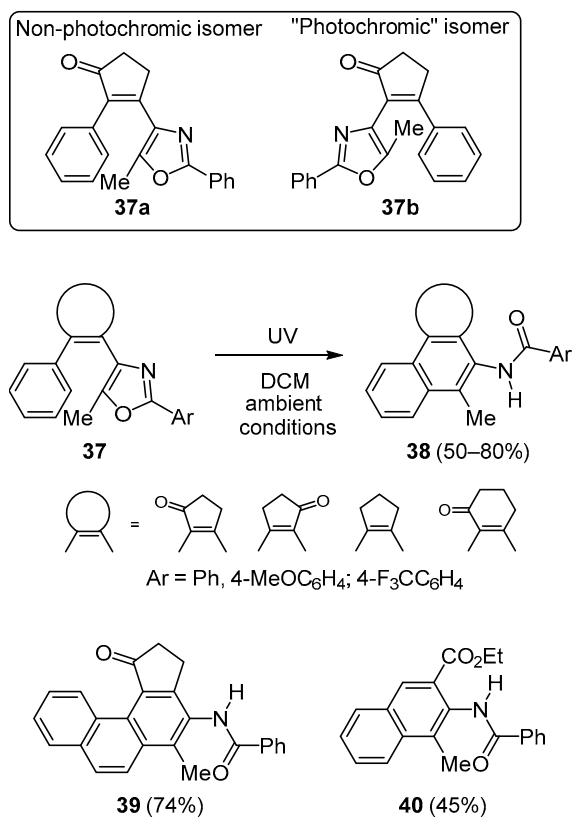
Photochromic isomer



A few cycles, poor stability

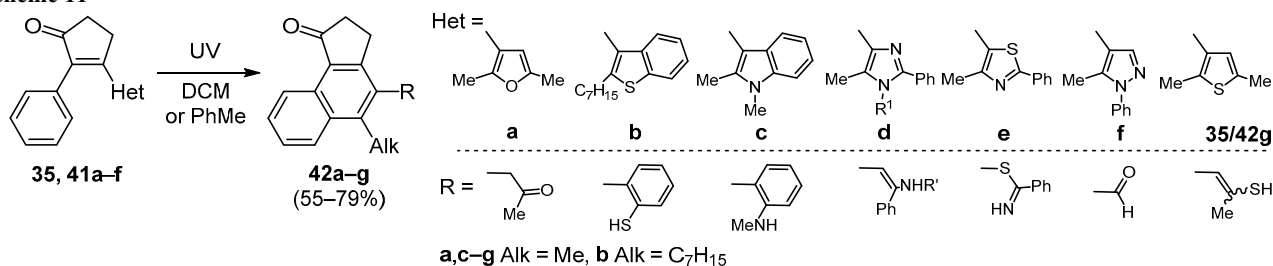
Subsequently, we observed this trend also for the oxazole analogs **37a,b** (Scheme 10).⁴¹ The analysis of their photoactivity showed that these isomers, as well as a series of other structurally related diarylethenes **37** underwent photorearrangement to naphthalene derivatives **38**. The process was easily scalable to 200 mg, did not require inert atmosphere, and the final product was conveniently purified. This reaction could be used for the preparation of phenanthrene **39** and naphthalene **40** from the respective diarylethenes. At this stage, we noticed a trend that diarylethenes containing a carbonyl group at the geminal position relative to the phenyl substituent at the double bond (e.g., compound **37a**) did not form the colored isomer (it was not detected) and produced naphthalenes in higher yields, compared to their isomers (e.g., **37b**).

Scheme 10



We further showed that this reaction was generally applicable and could be performed with derivatives of various five-membered heterocycles **41** (Scheme 11).⁴² The naphthalenes **42** with various functional groups, existing in masked form in the starting heterocycle, were formed in

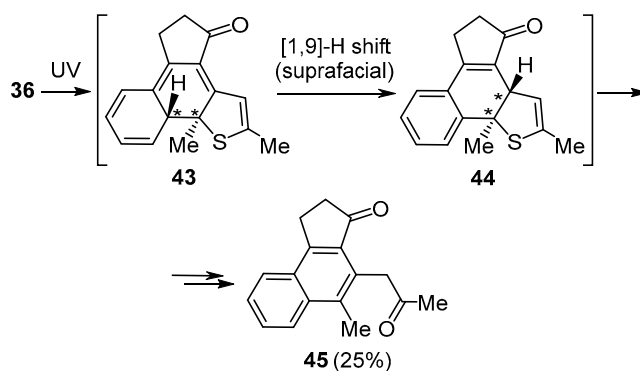
Scheme 11



these reactions with moderate to high yields. It should be noted that all these examples involved a cleavage of carbon–heteroatom bond.

At this stage we were able to interpret the previously obtained experimental data for compounds **35** and **36** (Scheme 9). The "photochromic" isomer **36** was converted to the photoinduced form **43** upon irradiation (Scheme 12), which could be detected by electronic spectroscopy.⁴² This intermediate underwent a very fast thermal transformation, interpreted as thermally allowed suprafacial [1,9]-hydrogen shift according to the principles of orbital symmetry conservation,⁴³ giving compound **44**. Carrying out this procedure preparatively, we have isolated the final product of the cascade transformation, naphthalene **45**. Under similar conditions the non-photochromic isomer **35** gives the corresponding naphthalene **42g** with 70% yield (Scheme 11).

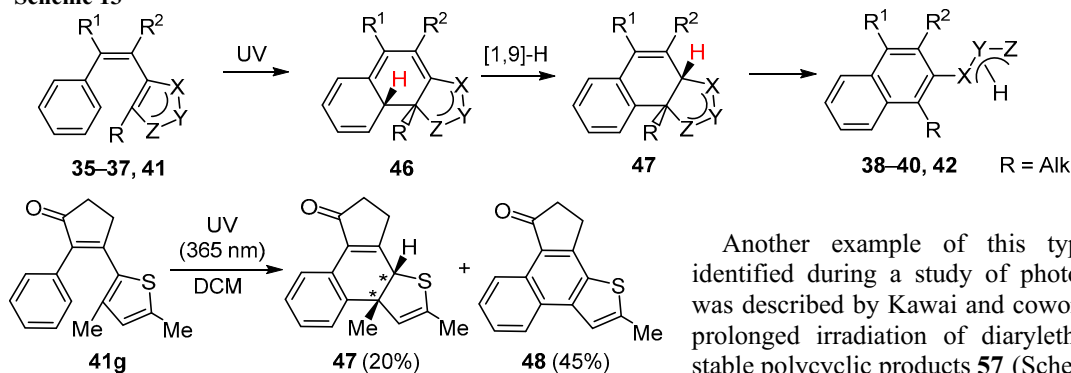
Scheme 12



We established the mechanism of this reaction based on the literature data and our experimental results (Scheme 13). The primary photocyclization product **46** underwent a thermal [1,9]-sigmatropic shift leading to compound **47**, which underwent rearomatization to the final products. Additional confirmation of this mechanism was obtained from photolysis of diarylethene **41g**, giving compound **47** in 20% isolated yield as a product of [1,9]-sigmatropic shift followed by isomerization to the more stable isomer. Another product of this reaction was compound **48**, an isosteric analog of phenanthrene that was formed by elimination of methane.

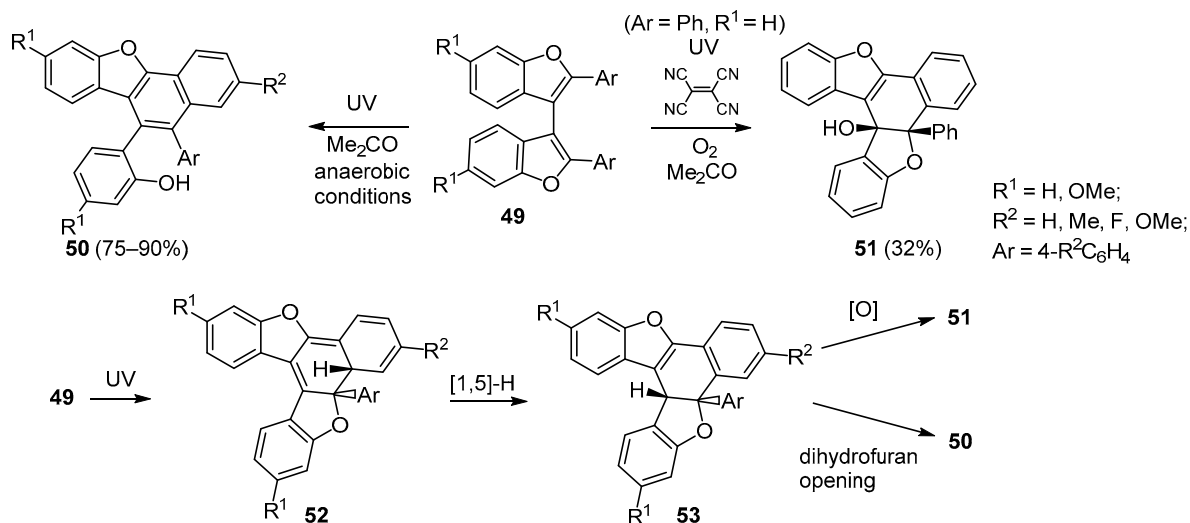
These data are relevant for the design of photochromic diarylethenes (due to the obvious importance of hydrogen atom at the reactive positions of aromatic substituents), as shown by us in the case of diarylethenes with modulated fluorescence.⁴⁴

Scheme 13

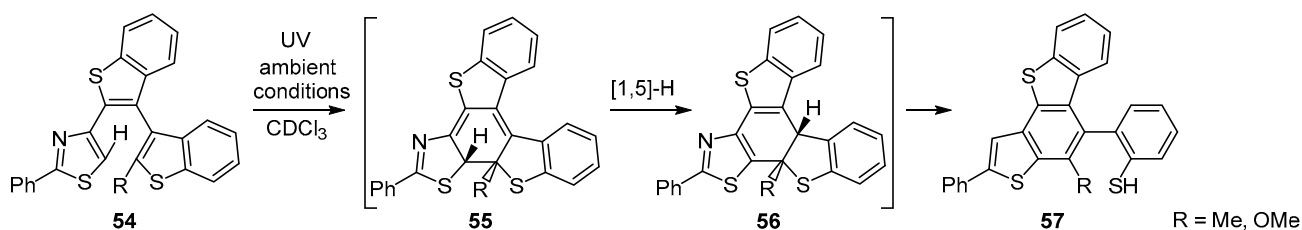


In studying the fluorescence properties of 3,3'-bis(arylbenzofurans), Wegner with coworkers demonstrated that some of those compounds were subject to photolysis.⁴⁵ The photoreaction of compounds **49** under inert atmosphere led to polyaromatic products **50** in high yields (Scheme 14). At the same time, the authors showed that the oxidation product **51** was formed in the presence of oxygen and tetracyanoethene as sensitizer. Unfortunately, the reaction was not tested in the presence of air oxygen without any sensitizer. The authors proposed a reaction mechanism based on electrocyclicization of hexatriene system followed by hydrogen migration, accompanied by opening of the heterocycle. This mechanism can be refined, including a step of [1,5]-sigmatropic shift in the primary intermediate **52**, leading to the formation of compound **53**, rearomatization or oxidation of which gives the final products **50**, **51** (Scheme 14).

Scheme 14



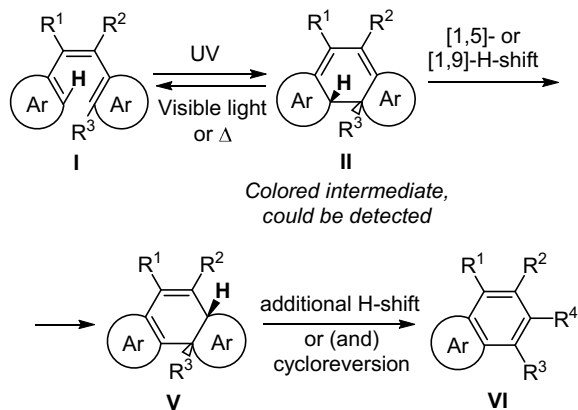
Scheme 15



Another example of this type of rearrangements, identified during a study of photochromic diarylethenes, was described by Kawai and coworkers.⁴⁶ They found that prolonged irradiation of diarylethenes **54** produced the stable polycyclic products **57** (Scheme 15). The mechanism for the formation of polycyclic compounds **57** included photocyclization and [1,5]-sigmatropic hydrogen shift, followed by rearomatization. It was shown by NMR spectroscopy that the reaction occurred with quantitative yield, even in the presence of air oxygen. An important feature was that the rearrangement also occurred when there was a methoxy group at the reaction center of hexatriene system, i.e., when there was no elimination of methanol,²⁵ allowing to significantly expand the possibilities for obtaining functionalized polyaromatic compounds.

The transformations described above can be generally illustrated with Scheme 16. In those cases when the substituents at the photoreaction centers are hydrogen atoms, the reaction required inert conditions to prevent oxidation, while in the rest of the cases the reaction could be performed in the presence of air oxygen. The UV-induced photocyclization of hexatriene system led to the formation of colored intermediate **II** containing a

Scheme 16



conjugated system of double bonds, which, depending on its stability, could be detected by electronic spectroscopy or flash photolysis (it should be noted that a colored intermediate could be detected at low temperature during the related cascade reaction of vinyl biaryls, consisting of photocyclization and [1,5]-sigmatropic shift.⁴⁷

The further [1,5]- or [1,9]-sigmatropic hydrogen shift led to the formation of structure V. The effectiveness of these processes was largely determined by restoration of aromaticity in one of the rings. Theoretical examination of the related cascade transformations of vinyl biaryls indicated a direct effect of aromaticity on the rate of [1,5]-sigmatropic shift.⁴⁸ This result was principally important, because in all of the aforementioned examples 6π -electron system was restored by hydrogen migration. Another factor affecting the stability of primary intermediate II was the nature of substituents in the ethene "bridge". For example, the conjugation of migrating proton in the intermediate II with an electron-withdrawing carbonyl group led to significant acceleration of the reaction and prevented the detection of this intermediate under the usual conditions.⁴¹ The outcome of synthesis was substantially affected by the presence of acids or bases. The general synthetic value of the described transformations is in the potential for assembling a broad range of polyaromatic compounds with various functional groups. The possibility of performing this type of reactions with a wide range of compounds (stilbenes, diarylethenes, dihetarylethenes, terarylenes, merocyanines, fulgides, fulgimides, and others) containing a 1,3,5-hexatriene system provides opportunities for using this type of photoinduced reactions as capable synthetic tools.

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