

Recent Advances in Di- π -methane Processes. Novel Reactions of 1,4-Unsaturated Compounds Promoted by Triplet Sensitization and Photoelectron Transfer

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Recent studies on the photoreactivity of 1,4-unsaturated systems have changed some ideas that were firmly established in this area of research for many years. Thus, we have described the first examples of 2-aza-di- π -methane (2-ADPM) rearrangements promoted by triplet-sensitization and by single electron transfer (SET) using electron-acceptor sensitizers. These reactions afford *N*-vinylaziridine and cyclopropylimine photoproducts in the first examples of di- π -methane processes that yield three-membered ring heterocycles. 1-Aza-1,4-dienes also undergo SET-promoted 1-aza-di- π -methane (1-ADPM) rearrangements *via* radical-cation intermediates using electron acceptor sensitizers. In some cases, alternative cyclizations yielding different carbocycles and heterocycles have been observed. The 1-ADPM and di- π -methane (DPM) reactions also occur *via* radical-anion intermediates on irradiation using electron donor sensitizers. On the other hand, the photoreactivity reported for β,γ -unsaturated aldehydes for many years was decarbonylation to the corresponding alkenes. However, our studies demonstrate that these compounds undergo the oxa-di- π -methane (ODPM) rearrangement with high chemical and quantum efficiency. A comparison of the photochemical reactivity of β,γ -unsaturated aldehydes and corresponding methyl ketones has shown that the ketones do not undergo the ODPM rearrangement while the corresponding aldehydes are reactive by this pathway. Monosubstituted β,γ -unsaturated aldehydes at C-2 undergo the ODPM rearrangement yielding the corresponding cyclopropane carbaldehydes diastereoselectively. Finally, we have described the first examples of reactions, similar to the well known Norrish Type I process, which take place in the triplet excited state of β,γ -unsaturated carbonyl compounds by excitation of the C-C double bond instead of the carbonyl group.

key words: Di- π -methane rearrangements, Single electron transfer, Radical-cations, Radical-anions, Cyclopropanes, Vinylaziridines

INTRODUCTION

Studies on the photoreactivity of 1,4-unsaturated compounds have been one of the main areas of research in organic photochemistry for more than thirty years. Substances in this family undergo unique and synthetically useful photoreactions. Examples of this are found in di- π -methane (DPM) rearrangements of 1,4-dienes [1,2], oxa-di- π -methane (ODPM) photoreactions and 1,3-acyl migration processes of β,γ -unsaturated ketones [1,3-6], and the 1-aza-di- π -methane (1-ADPM) rearrangements of 1-aza-1,4-dienes [1,7,8]. The studies carried out by a large number of research groups worldwide on these three types of di- π -methane reactions have shown that they are very general and usually take place with high chemical and quantum efficiency, affording cyclopropane derivatives that, in many instances, are difficult to obtain, or not available, by alternative routes. The influence of substitution, scope and mechanistic features of these rearrangements were clearly established. In addition, a high degree of stereoselectivity

was observed in many instances, therefore, it is not surprising that these reactions have been applied as the key step in the synthesis of natural products and complex molecules [6].

The results obtained had also established other general features of these rearrangements. Some of them can be summarized as follows: (a) Di- π -methane rearrangements were typical examples of reactions that occurred in the excited state exclusively. These rearrangements were never observed in the ground state chemistry of 1,4-unsaturated compounds. (b) Concerted or biradical mechanisms were postulated to justify these rearrangements in all the cases studied. There was no data that suggested the involvement of other intermediates in these processes. (c) Di- π -methane rearrangements always yielded cyclopropane derivatives. Three membered ring heterocycles that could be formed in the ODPM and 1-ADPM processes were never observed. (d) The ODPM rearrangement was restricted to β,γ -unsaturated ketones. The corresponding aldehydes underwent decarbonylation on direct and sensitized irradiation, with two exceptions only.

As a consequence of all the information accumulated on these rearrangements up to 1995, there was the general impression from the majority of organic photochemists that the photoreactivity of 1,4-unsaturated systems was well established

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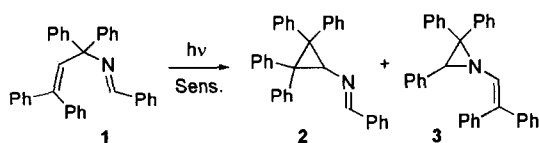
and totally predictable in most cases and, therefore, there was very little to uncover in this area of research.

However, studies carried out in our laboratory in recent years have demonstrated that some of the ideas that were firmly established on the reactivity of β,γ -unsaturated compound were incorrect. The following sections summarize some of the changes that have taken place in this area of research as a result of our findings.

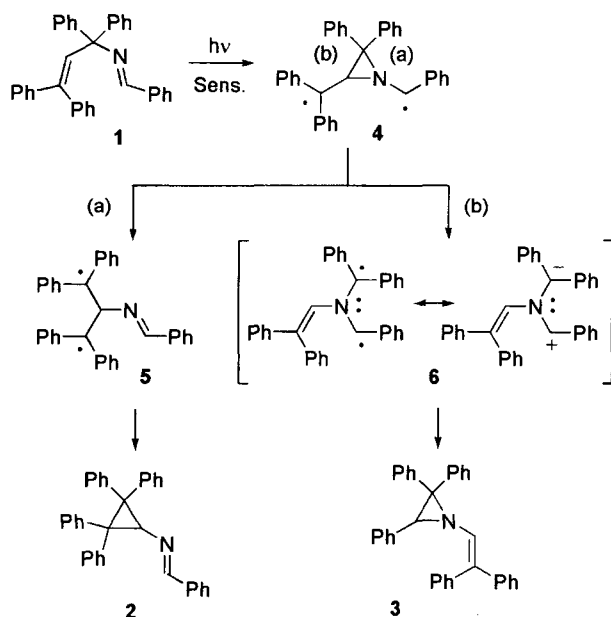
DISCUSSION

The 2-ADPM Rearrangement Promoted by Triplet-Sensitization

As mentioned above, di- π -methane reactions were restricted to 1,4-dienes, β,γ -unsaturated ketones and 1-aza-1,4-dienes for many years [1-8]. However, in 1997 we reported the first example of a 2-aza-di- π -methane rearrangement (2-ADPM) in the triplet-sensitized irradiation of the 2-azadiene **1** that yielded the cyclopropylimine **2** and the *N*-vinylaziridine **3** (Scheme 1) [9]. The mechanism shown in scheme 2 was proposed to account for the reaction. This involves the generation and competitive cleavage of aziridinyldicarbonyl biradical **4**. Thus, the major photoproduct **2** is formed by C-N bond cleavage in **4**, which affords the 1,3-biradical **5** that



Scheme 1.



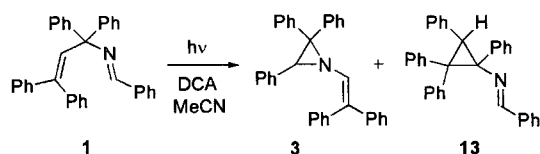
Scheme 2.

cyclize to generate cyclopropylimine **2** (path a). Competitive C-C bond fragmentation in **4** provides the intermediate **6**, the precursor of the vinylaziridine **3** (path b). This photoreaction represents the first example of a 2-aza-di- π -methane rearrangement that occurs *via* a three membered ring heterocyclic biradical and brings about the formation of a heterocyclic product. It is worth noting that intermediate **6** could be either a triplet 1,3-biradical or a singlet azomethine ylide, depending on whether or not ISC occurs prior to C-N bond cleavage in **4**. Only the singlet azomethine ylide is capable of undergoing cyclization to form **3**. The 2-ADPM reaction is not restricted to compound **1** and 2-azadienes **7a**, **7b** and **8** also undergo triplet-sensitized rearrangement to the corresponding cyclopropylimines **9a**, **9b** and **10**, in low yield. In these instances the corresponding *N*-vinylaziridines are not formed (D. Armesto *et al.*, unpublished). The reasons for this regioselectivity are unclear at this point, but it is obvious that dimethyl substitution at the methane carbon in the 2-aza-1,4-diene system suppresses the formation of the corresponding *N*-vinylaziridines. This observation supports the idea that the relative rates of ring opening reactions of the biradical intermediates are governed by the relative stability of the formed azomethine ylides and 2-imino-1,3-biradicals.

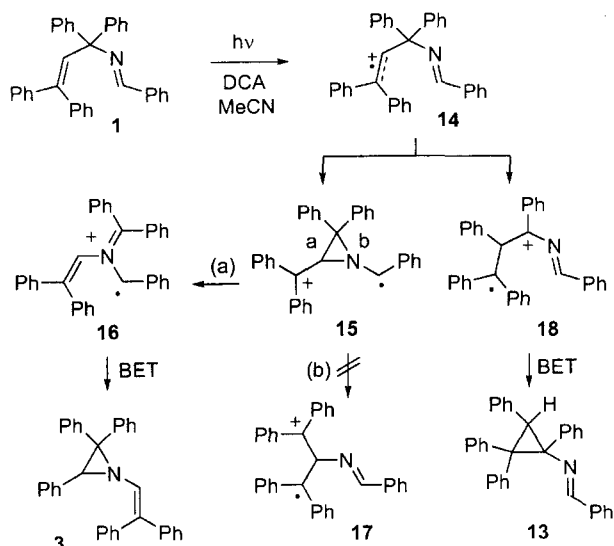
The results outlined above clearly demonstrate that di- π -methane rearrangement are not restricted to the β,γ -unsaturated systems studied before, but can be extended to 2-aza-1,4-dienes which undergo novel photochemical reactions to produce small-ring carbo- and *N*-heterocyclic products. A highlight of this effort is the observation of the first example of a 2-aza-di- π -methane rearrangement yielding a vinylaziridine photoproduct.

The 2-ADPM Rearrangement Promoted by Electron-Acceptor Sensitizers

A surprising result was obtained in the study of the photoreactivity of 2-aza-1,4-dienes using 9,10-dicyanoanthracene (DCA) as electron-acceptor sensitizer. Direct or triplet sensitized irradiations have been used to promote the di- π -methane rearrangement of 1,4-unsaturated compounds. However, Zimmerman and Hoffacker have reported the DCA-sensitized irradiation of aryl-substituted 1,4-pentadienes **11** [10]. Under these conditions compounds **11** do not undergo the DPM rearrangement, yielding the corresponding benzhydryldihydronaphthalene derivatives **12**, instead. However, when compound **1** was irradiated using DCA as a SET-sensitizer the vinylaziridine **3** and the cyclopropylimine **13** were obtained, as shown in scheme 3. These reactions represent the first examples of SET-promoted rearrangements in 1,4-unsaturated systems (a 2-ADPM reaction generating **3** and an aryl-di- π -methane rearrangement yielding **13**) that afford three membered ring products [9]. Of equal interest is the fact that vinylaziridine **3** is obtained in both the triplet- and SET-sensitized photoreactions of **1**. The products generated in this photoreaction appear to be consistent with the operation of a pathway, in which an initially formed olefin-localized cation-radical intermediate **14** bridges by C-N bond formation to give aziridinyldicarbonyl



Scheme 3.

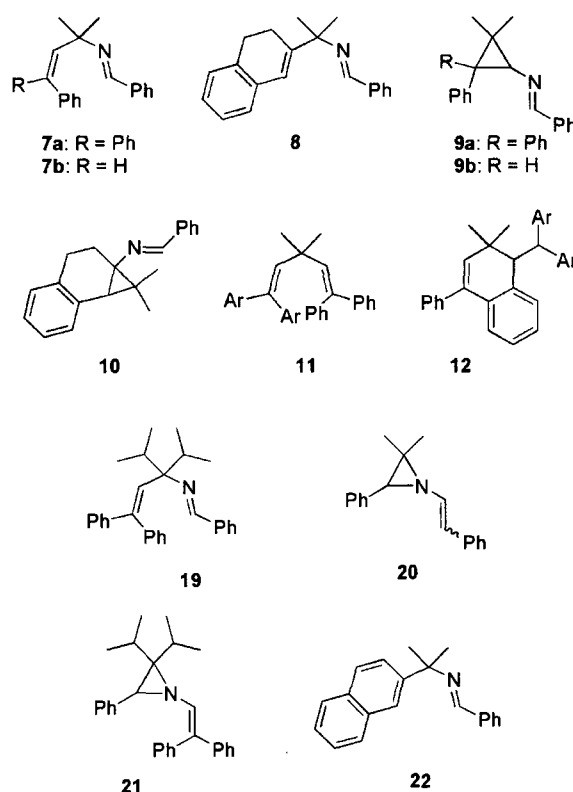


Scheme 4.

radical **15**. Ring opening in **15** by path (a) generates **16**, which by back electron transfer and biradical cyclization yields **3**. The alternative ring opening of **15** by path (b), which would have produced the corresponding cyclopropylimine, does not occur probably because the intermediate radical-cation **17** is less stable than **16**. A competitive route, involving phenyl migration in **14** generates cation-radical **18**, the precursor of **13** (Scheme 4).

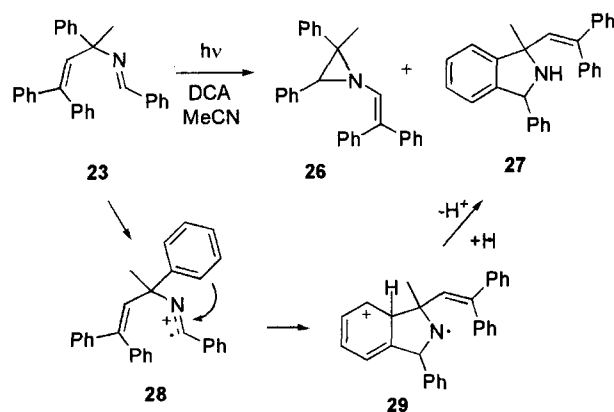
This study was extended to azadienes **7a**, **7b**, **8** and **19**. DCA-sensitized irradiation of azadienes **7b** and **19** afforded the corresponding *N*-vinylaziridines **20** and **21**, respectively. However, under these reaction conditions, compound **7a** yielded a complex mixture of products in which the corresponding vinylaziridine was not present and azadiene **8** gave the naphthalene derivative **22** resulting from aromatization of the dihydronaphthalene unit. This observation shows that oxidation of the dihydronaphthalene moiety takes preference over the 2-ADPM reaction (D. Armesto *et al.*, unpublished).

These results demonstrate that the novel 2-ADPM rearrangement of 2-aza-1,4-dienes to *N*-vinylaziridines via radical-cation intermediates is not restricted to compound **1** but can be extended to azadienes **7b** and **19**. However, there are clear differences between the 2-ADPM rearrangement in the triplet excited state and the corresponding reaction via radical-cation intermediates. Probably the most important one is the regioselectivity observed. Thus, while the triplet reaction

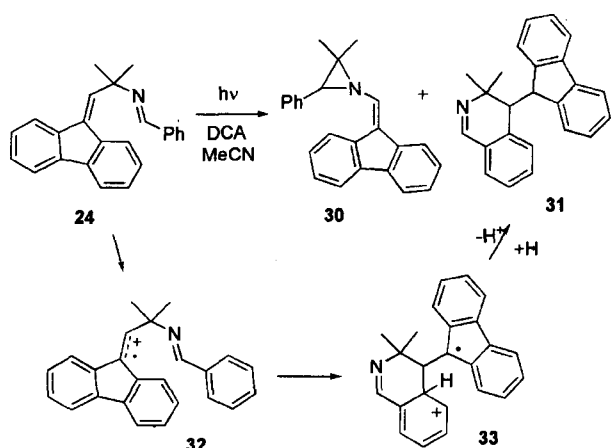


yields cyclopropylimines, with one exception only, the SET-rearrangement affords the corresponding *N*-vinylaziridines. The reasons for the triplet regioselectivity are still unclear but the formation of the vinylaziridines can be easily explained based on the differences in stability between the two possible radical-cation intermediates resulting from the ring opening of the intermediate aziridiny radical-cation (Scheme 4).

Searching for additional examples of the 2-ADPM-SET rearrangement the study was extended to azadienes **23**, **24**, **25a** and **25b**. DCA-sensitized irradiation of **23** afforded the *N*-vinylaziridine **26** and a new product that was identified as the 2,3-dihydro-1*H*-isoindole **27** (Scheme 5). The formation of **27**



Scheme 5.

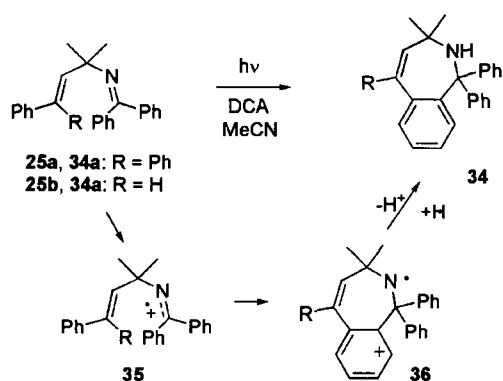


Scheme 6.

is in accord with the operation of a mechanistic pathway involving the generation of an imine-localized radical-cation intermediate **28** that, by electrophilic attack to the phenyl ring at the methane carbon, affords the cyclic radical-cation **29**, the precursor of **27** (Scheme 5).

Irradiation of **24**, under the above conditions, afforded the *N*-vinylaziridine **30** and a new compound that was identified as the dihydroisoquinoline **31** (Scheme 6). The latter product is formed by electrophilic addition of the olefin-localized radical-cation **32** on the phenyl ring at C-1 yielding intermediate **33**, the precursor of **31** (Scheme 6). This cyclization process is similar to the one observed by Zimmerman and Hoffacker in their study of the DCA-sensitized irradiation of the aryl-substituted 1,4-pentadienes **11** [10].

In contrast, irradiation of compounds **25a** and **25b** under the above conditions for short time periods affords the corresponding dihydrobenzoazepines **34a** and **34b**, respectively, in high isolated yields (Scheme 7). The formation of compounds **34** is consistent with a mechanism involving the generation of an imine-localized radical-cation **35** that, by electrophilic attack to the phenyl ring at C-5, yields intermediate **36**, the precursor of **34** (Scheme 7). The high yields of products obtained in the



Scheme 7.

DCA-sensitized irradiation of compounds **25** suggest that this methodology might be applicable to the synthesis of dihydrobenzoazepines from β,γ -unsaturated ketoimines [11].

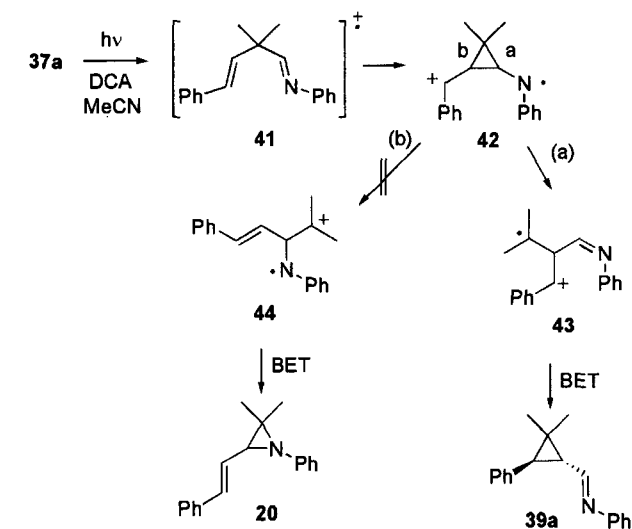
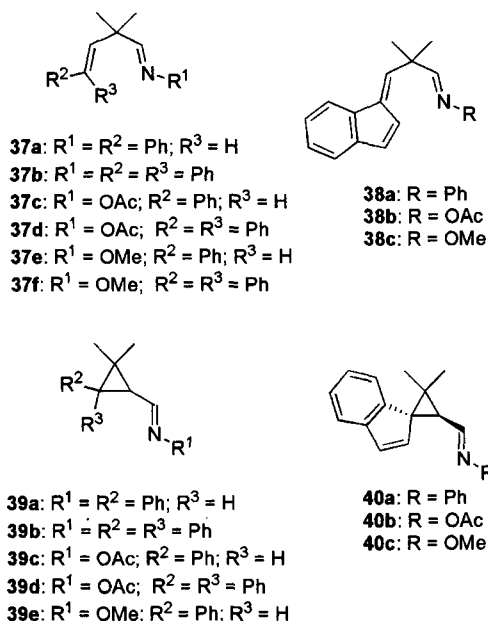
The results obtained in the SET-sensitized irradiation of azadienes **23**, **24** and **25** demonstrate that in addition to the 2-ADPM rearrangement to *N*-vinylaziridines, alternative cyclization paths are open to the radical-cation intermediates, yielding dihydroisoindoles, dihydroisoquinolines and dihydrobenzoazepines. Further studies are needed to determine if it is possible to control the outcome of the photoreactions by modifying the substituents present on the 2-azadiene's skeleton. Something worth noting regarding the formation of compounds **27**, **31** and **34** is that, while compounds **27** and **34** result from radical-cations centered in the imine moiety, the dihydroisoquinoline **31** is formed from a radical-cation centered in the alkene unit. This is somewhat surprising and demonstrates that two different radical-cations intermediates can be generated from the alkene and imine functional groups, which have different ionization potentials.

In summary, the results outlined above clearly demonstrate that 2-aza-1,4-dienes undergo novel photochemical reactions. Our studies of the triplet-sensitized photoreactions of these compounds has led us to uncover the first examples of 2-ADPM rearrangements that yield cyclopropylimines. In the case of azadiene **1**, the reaction also affords the *N*-vinylaziridine **3**, representing the first example of a di- π -methane rearrangement that yields a three-membered ring heterocyclic photoproduct. A more significant conclusion of this study is that 2-ADPM rearrangements can also take place under SET-sensitized irradiation conditions to generate *N*-vinylaziridines regioselectively. In the case of azadiene **1**, cyclopropylimine **13**, resulting from an aryl-di- π -methane reaction *via* a radical-cation intermediate, is observed. Alternative cyclization modes have been detected in some instances yielding dihydroisoindoles and dihydroisoquinolines. Ketoimines **25** do not undergo the 2-ADPM rearrangement but, rather react to produce the corresponding dihydrobenzoazepines **34** in good yield. It is our belief that the results coming from these studies have led to new views of an old but still important photochemical rearrangement process.

1-ADPM Rearrangement Promoted by Electron-Acceptor Sensitizers

The results obtained in the SET-sensitized irradiation of 2-aza-1,4-dienes using DCA as an electron acceptor sensitizer suggested that other β,γ -unsaturated compounds might also be capable of participating in di- π -methane type rearrangements *via* radical-cation intermediates. In order to test this proposal, we have carried out a study on a series of 1-substituted-1-aza-1,4-dienes. The results obtained demonstrate that these compounds undergo novel 1-ADPM rearrangements *via* radical-cations using DCA, or dicyanodurene (DCD), as electron acceptor sensitizers [11].

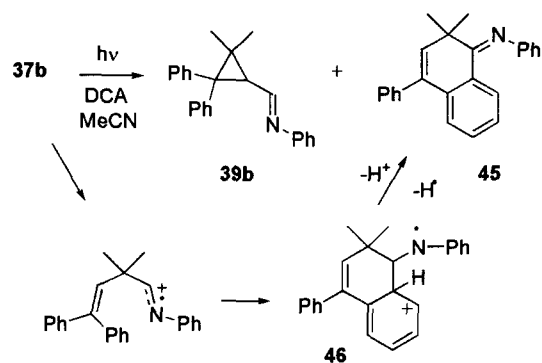
The compounds selected for this study were the imines **37a**,



Scheme 8.

37b and **38a**. DCA-sensitized irradiation of these imines yielded the corresponding cyclopropylimines **39a**, **39b** and **40a**. This result demonstrates clearly that, like the 2-aza-1,4-dienes analogues, 1-aza-1,4-dienes also undergo a di- π -methane type radical-cation rearrangement reaction.

The mechanism shown in scheme 8 for imine **37a** could account for the formation of the 1-ADPM products. It involves the generation of the radical-cation intermediate **41** that bridges across to give the cyclopropyl radical-cation **42**. Ring opening of bond (a) in **42** generates **43**, which by back electron transfer and biradical cyclization, yields **39a**. The alternative cleavage of bond (b) that would have yielded the vinylaziridine **20** is not observed owing to the fact that the resulting radical-cation

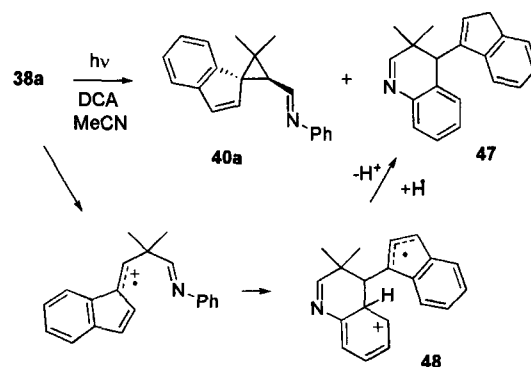


Scheme 9.

44 would be considerably less stable than intermediate **43**.

Irradiation of imine **37b** afforded, in addition to the cyclopropylimine **39b**, a new compound that was identified as the dihydronaphthalene derivative **45** (Scheme 9). This result shows that two different reaction paths are open to the radical-cation intermediate derived from **37b**. The first involves 1-ADPM rearrangement leading to **39b** and the other is promoted by cyclization affording **45**. A possible mechanism to justify the formation of **45** could involve intramolecular electrophilic attack of a radical-cation centered in the C-N double bond to one of the phenyl ring at C-5 to afford the intermediate **46**, which loses a proton and a hydrogen radical yielding **45** (Scheme 9). As mentioned before, Zimmerman and his coworkers have observed a similar cyclization process in their study of the electron-acceptor sensitized photoreactions of 1,4-dienes **11** which yield benzhydryldihydronaphthalenes **12** [10]. However, it is interesting to note that dienes **11** do not undergo radical-cation rearrangements of the di- π -methane type.

Irradiation of imine **38a**, under the same conditions used for **37a** and **37b**, yielded, in addition to the cyclopropylimine **40a**, the dihydroquinoline **47**. The mechanism shown in scheme 10 accounts for the formation of dihydroquinoline **47**. In this instance, an olefin-centered radical-cation undergoes intramolecular electrophilic addition to a phenyl ring at C-1,



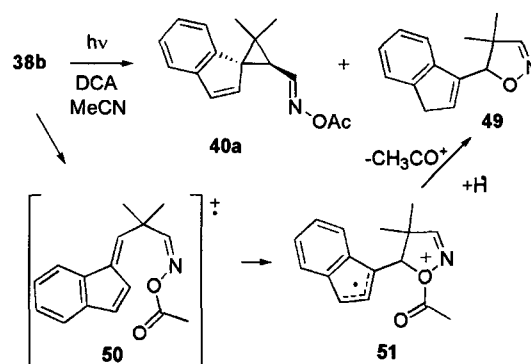
Scheme 10.

generating the intermediate **48**, which by aromatization and hydrogen abstraction, yields **47**.

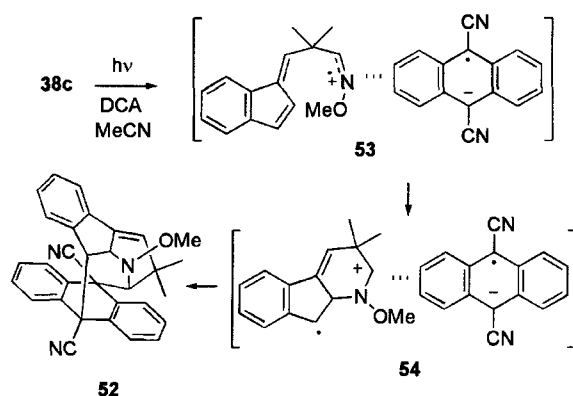
The results obtained from studies of the DCA-sensitized photoreactions of imines **37a-b** and **38a** demonstrate that these compounds react to afford the corresponding cyclopropylimines **39a-b** and **40a**. These processes represent second examples of di- π -methane type rearrangements that take place *via* radical-cation intermediates. However, other photoproducts are also obtained in the photoreactions of **37b** and **38a**. These are the dihydronaphthalene derivative **45** and the dihydroquinoline **47**, respectively. With regard to the formation of these two products, it is worth noting that while compound **45** results from a radical-cation centered in the imine moiety, the quinoline **47** is formed from a radical-cation centered in the alkene unit. These results are similar to those mentioned before for the 2-azadienes **23**, **24** and **25**, supporting the idea that, under SET-sensitized irradiation, two different and competitively reactive radical-cations intermediates are generated from two donor centers with different ionization potentials (the alkene and the imine).

Our attention was next directed at determining whether or not the reaction could be extended to other 1-aza-1,4-dienes in which the C=N bond would be less readily hydrolyzed thus facilitating handling and isolation of starting materials and photoproducts. Our previous studies of the 1-ADPM rearrangement have demonstrated that β,γ -unsaturated oxime acetates rearrange more efficiently than do the corresponding imines in the triplet excited state [1,7,8]. In addition, the reactants and products of these processes are sufficiently stable to allow for their isolation by silica gel chromatography. Oxime ethers are another type of C=N derivatives stable towards hydrolysis. Consequently, our studies of SET-sensitized photoreactions were extended to the oxime acetates **37c**, **37d**, and **38b** and also to the oxime ethers **37e**, **37f** and **38c**, which are structurally related to the imines **37a-b** and **38a**, respectively. DCA-sensitized irradiation of compounds **37c-d** and **38b** afforded the corresponding cyclopropanes **39c**, **39d** and **40b**, respectively, resulting from 1-ADPM rearrangements. These results show that the 1-ADPM rearrangement *via* radical-cation intermediates can be extended to β,γ -unsaturated oxime acetates. The qualitative efficiencies of the reactions of oxime acetates **37c-d** and **38b** and the yields of products are clearly higher than those for the imines **37a-b** and **38a**. Irradiation of oxime acetate **38b** gives, in addition to the cyclopropane **40b**, a new product that was identified as the dihydroisoxazole **49**. A possible mechanism to justify formation of **49** involves cyclization within the radical-cation **50** to generate the intermediate **51**, which by elimination of acetic acid yields **49** (Scheme 11). In this instance it is difficult to know whether the reaction is promoted by a radical-cation centered in either the alkene or the oxime acetate moieties.

DCA-sensitized irradiation of oxime ether **37e** promotes formation of the 1-ADPM rearrangement derived cyclopropane **39e**. However, irradiation of **37f**, under the same conditions



Scheme 11.



Scheme 12.

used for **37e**, gives recovered starting material and a complex mixture of products that does not contain the corresponding 1-ADPM product. Finally, when oxime ether **38c** was irradiated under the above conditions yielded the spirocyclopropane **40c** and a new compound that was identified as the [4+4]-cycloadduct **52** by using X-ray diffraction analysis.

A possible mechanism for formation of **52** involves the generation of radical-cation/radical-anion pair **53**. Intramolecular cyclization of the radical-cation within the solvent cage generates the radical-cation/radical-anion pair **54**, which by intermolecular cycloaddition yields **52** (Scheme 12).

The results obtained in studies with β,γ -unsaturated oxime ethers **37e** and **38c** show that these undergo the 1-ADPM rearrangement *via* radical-cation intermediates in low yields. The formation of cycloadduct **52** from **38c** is surprising and it demonstrates that unexpected alternative reaction routes are opened to the intermediate radical-cations in some instances.

The results summarized thus far indicate that 1-substituted-1-aza-1,4-dienes undergo 1-ADPM rearrangements upon irradiation using DCA as an electron-acceptor sensitizer. However, from a synthetic point of view these reactions have little interest since the product yields are usually low. Previous studies have shown that SET-photoreaction sensitized by dicyanodurene (DCD) often occur with higher yields [12]. In

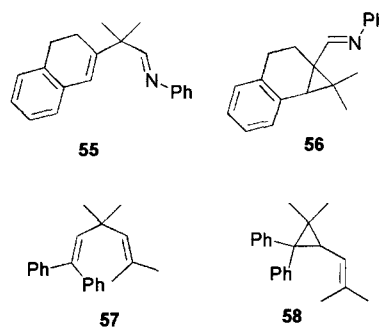
an attempt to increase the yield of products we have explored the photoreactivity of the 1-aza-1,4-dienes using DCD as electron-acceptor sensitizer. The results obtained, show that reaction, under these conditions, require shorter irradiation times in most cases and result in increased yields of the 1-ADPM photoproducts [11b].

For instance, DCA-sensitized irradiation of oxime acetate **37c**, for 2.5 h, affords cyclopropane **39c** in 15% yield, while DCD-sensitized reaction of this substance for 1 h gives **39c** in a 60% yield. Similar enhancements in the yields of 1-ADPM products occur with the other substances. These results show that apart from the mechanistic interest, 1-ADPM rearrangements promoted by electron acceptor sensitizer can be used for synthetic purposes.

We believe that the rearrangements of the di- π -methane type observed in the DCA-sensitized irradiations of 1-aza- and 2-aza-1,4-dienes are important because the di- π -methane process has been considered until now a paradigm of reactions that take place in the excited state manifold only. Our results show that rearrangements of this type can also occur in the ground-states of radical-cation intermediates. This opens the possibility of promoting di- π -methane type rearrangements by alternative thermal means.

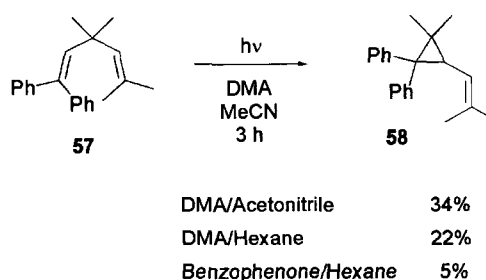
Di- π -Methane Rearrangements Promoted by Electron-Donor Sensitizers

The 1-ADPM and 2-ADPM rearrangements of aza-1,4-dienes *via* radical-cations suggested the possibility that other radical ion intermediates (*e.g.*, radical-anions) could also be responsible for this rearrangement reaction. In order to test this proposal, azadienes **37a-b**, **38a** and **55** were irradiated in acetonitrile using *N,N*-dimethylaniline (DMA) as an electron acceptor sensitizer. Under these conditions the corresponding cyclopropylimines **39a-b**, **40a** and **56** were obtained [13]. These results clearly show that 1-ADPM rearrangements of azadienes **37a-b**, **38a** and **55** can be photosensitized by DMA, a well known electron-donor [14]. However, the possible involvement of radical-anions in these reactions is tentative since we previously observed triplet 1-ADPM reactivity of azadiene **37b** by using acetophenone as sensitizer [15]. Since the DMA has a triplet energy of 68.4 kcal/mol [14], efficient energy transfer to the diphenylvinyl unit (*ca.* triplet energy of 53-62 kcal/mol [16]) is possible in these processes. The question that arises is whether or not the DMA sensitized reactions take place *via* SET or triplet energy transfer mechanisms. In order to clarify this issue, azadienes **37a-b**, **38a** and **55** were irradiated for the same period of time, by using DMA in the non-polar solvent hexane. Under this condition, radical anion formation should not be favored. We observed that DMA sensitized reactions of **37a-b** and **38a** takes place in hexane to yield the corresponding cyclopropylimines **39a-b** and **40a**, respectively in very low yields [13]. This result supports the proposal that radical-anions are involved as intermediates in photoreactions in acetonitrile.

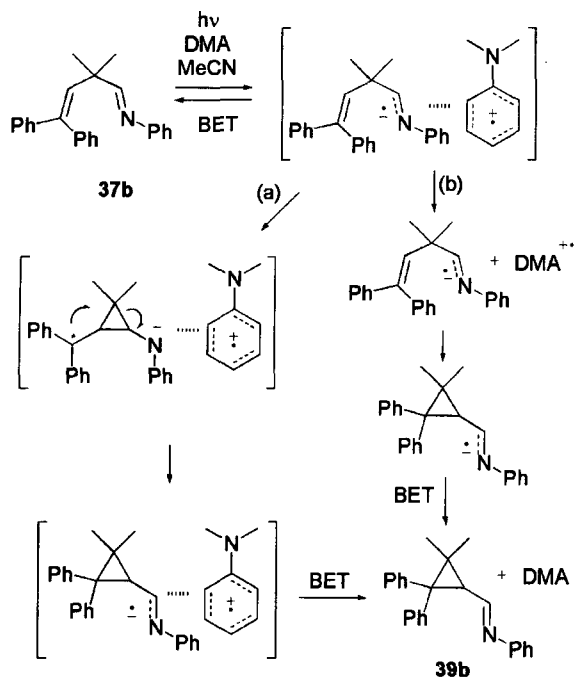


However, in the case of compound **55**, the yields of cyclopropane **56** from the acetonitrile and hexane reactions were similar, casting doubts again on whether or not this process occurs *via* SET or triplet energy sensitization.

In an attempt to obtain a more definite answer to this question, we searched for a substrate that would not undergo the di- π -methane rearrangement in the triplet excited state manifold. With this goal in mind, the study was extended to the 1,4-diene **57**. A study on the photochemical reactivity of **57** by Zimmerman and Pratt showed that it rearranges efficiently to yield the cyclopropane **58** on direct irradiation [17]. However, the process is very inefficient when benzophenone triplet sensitization is used. Therefore, compound **57** was considered to be a good candidate to test the possibility of promoting di- π -methane reactions by using electron-donor sensitizers. Irradiation of **57** in acetonitrile, for 3 h, by using DMA as a sensitizer, yielded cyclopropane **58** in 34% yield (Scheme 13). Changing the solvent from acetonitrile to hexane does not modify significantly the efficiency (22%) of the process. However, when diene **57** was irradiated in hexane for 3h, with benzophenone as sensitizer, the cyclopropane **58** was obtained in only 5% yield, in agreement with the earlier results [17]. Since the triplet energy of benzophenone (69.2 kcal/mol) [14] is comparable to the value reported for the DMA (68.4 kcal/mol) [14], both sensitizers should be able to transfer their triplet energy to the diphenylvinyl unit with the same efficiency. Therefore, the decrease in the yield of product observed in the reactions run in hexane, caused by changing the sensitizer from DMA to benzophenone, cannot be explained by less efficient triplet energy transfer from the benzophenone



Scheme 13.



Scheme 14.

to diene **57**. These results lead to the conclusion that rearrangement of **57** to the cyclopropane **58**, occurring in the reactions sensitized by DMA, must take place *via* radical-anion intermediates [13]. Considering that the C-N double bond in compounds **37a-b**, **38a** and **55** should be a better electron acceptor than the diphenylvinyl unit in **57** it is logical to assume that the rearrangement of the 1-azadienes also takes place *via* the same types of ion-radical intermediates.

A possible mechanism for these reactions is shown in scheme 14 for compound **37b**. The absence of a solvent polarity effect on the efficiency of photoreactions of **55** and **57** might be due to a very fast rearrangement of the radical-anion intermediate within solvent cages (Scheme 14, path a). In cases in which this intermediate escapes from the cage before rearrangement occurs, a significant influence of the polarity of the solvent would have been observed. This is the situation in DMA sensitized reactions of **37a-b** and **38a** (Scheme 14, path b) [13].

These results provide strong evidence in favor of the involvement of radical-anions in electron donor sensitized 1-ADPM rearrangements of azadienes **37a-b**, **38a** and **55** and also in the di- π -methane reaction of diene **57**. These observations open new lines of research in an area in which, due to the large number of studies carried out for more than thirty years, apparently there were very few things that remained to be uncovered. Further studies will be necessary to determine the scope and synthetic applications of these reactions.

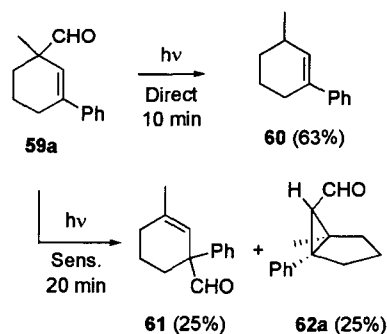
The ODPM Rearrangement of β,γ -Unsaturated Aldehydes

The photochemistry of carbonyl compounds has attracted

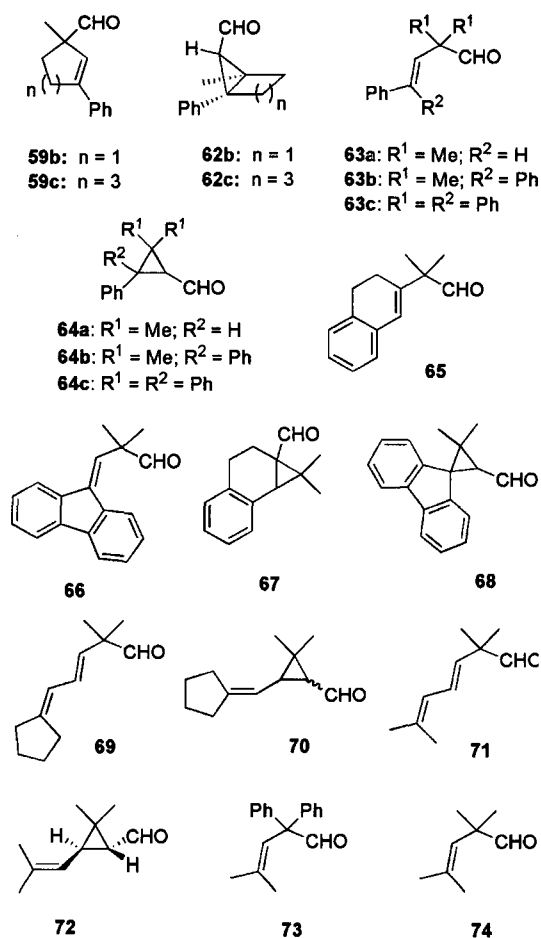
the interest of a large number of organic photochemists for many years [3-6]. The number of studies carried out on this class of compounds is much larger than on any of the other functional groups. Among all the different types of carbonyl compounds, β,γ -unsaturated ketones have been the subject of extensive studies. The results obtained show that, in simple terms, direct irradiation of β,γ -unsaturated ketones usually yields the corresponding 1,3-acyl migration product, whereas the triplet photochemical reactivity of these compounds brings about the formation of the corresponding cyclopropyl ketones by an ODPM rearrangement [3-5]. However, there are exceptions to this general rule, and some β,γ -unsaturated carbonyl compounds do not undergo the ODPM rearrangement [1]. The results of numerous studies suggest that β,γ -unsaturated aldehydes undergo only decarbonylation to form alkenes both on direct and sensitized irradiation [1]. There are only two examples of the occurrence of ODPM rearrangements on triplet-sensitized irradiation of β,γ -unsaturated aldehydes. One is found in a report by Schaffner *et al.* in 1966 [18] and the other by Zimmerman and Cassel in 1989 [19]. The combined results have led to a consensus opinion that β,γ -unsaturated aldehydes lack of ODPM photoreactivity [6].

However, these ideas have changed due to the results emanating from our recent studies. Thus, in an investigation of the application of the 1-ADPM rearrangement to the synthesis of bicyclo[n.1.0]alkanes by using ring contraction processes, an imine derivative of the aldehyde **59a**, was selected as the target molecule. Since the photochemistry of aldehyde **59a** was not described previously, it was important to first establish the photochemical behaviour of this compound and to compare its reactivity with that of the corresponding 1-aza-1,4-diene derivatives. We observed that direct irradiation of **59a** afforded a new product identified as the cyclohexene **60** which results from decarbonylation of aldehyde **59a** (Scheme 15). This result was not surprising based on the literature precedents mentioned above. In contrast, however, acetophenone-sensitized irradiation of **59a** afforded the 1,3-migration product **61** (25%) along with the ODPM product **62a** (25%) (Scheme 15) [20].

At this point it was difficult to explain the photoreactivity



Scheme 15.



observed in the irradiation of **59a**, although it was thought to be due to the influence of some unknown structural factors present in **59a**. Therefore, the study was extended to aldehydes **59b** and **59c** to determine whether this unexpected reactivity could also occur in other related aldehydes [20]. Acetophenone-sensitized irradiation of **59b** afforded the ODPM product **62b** in 90% isolated yield. Similarly, irradiation of **59c** under the same conditions gave the cyclopropyl aldehyde **62c** in 25% yield. In these two instances, the corresponding 1,3-formyl migration products were not formed.

In order to clarify whether or not the unexpected ODPM reactivity of aldehydes **59** was due to some structural factors present in these compounds we decided to study the photoreactivity of the β,γ -unsaturated aldehydes **63** which presents a substitution pattern that promotes the 1-ADPM rearrangement very efficiently. Triplet-sensitized irradiation of **63a**, for 15 min, afforded the cyclopropyl aldehyde **64a**, resulting from an ODPM rearrangement, as the *trans*-diastereoisomer, in 90% isolated yield. This result demonstrated clearly that the ODPM reactivity of β,γ -unsaturated aldehydes is not restricted to cyclic compounds, such as **59**, but can also be extended to acyclic derivatives [20].

The results obtained in the irradiations of aldehydes **59a-c**

and **63a** suggested that the main factor that controls the ODPM reactivity of these aldehydes is the stabilizing influence of phenyl groups on the bridging 1,4-biradical reaction intermediates. To confirm this hypothesis the photoreactivity of aldehydes **63b**, **63c**, **65** and **66**, in which the biradical intermediates are stabilized by conjugation with phenyl rings, was investigated. These substances undergo the ODPM rearrangement yielding the corresponding cyclopropyl aldehydes **64b** (57%), **64c** (82%), **67** (83%) and **68** (96%), respectively, after short irradiation times, according to our postulates [20].

The ODPM reactivity of β,γ -unsaturated aldehydes is not restricted to γ -phenyl-substituted compounds but can also be extended to systems in which the intermediate biradicals are stabilized by conjugation with a vinyl group. Thus, triplet-sensitized irradiation of **69** affords the cyclopropane derivative **70** as a 1:8 mixture of *cis:trans*-isomers. Similarly, irradiation of **71**, under the same conditions, yields **72** as the *trans*-isomer exclusively. In the absence of phenyl or vinyl substituents at the γ -position of the β,γ -unsaturated aldehyde the rearrangement can also take place, although very inefficiently. Thus, acetone-sensitized irradiation of aldehyde **73**, with diphenyl substitution at C-2, gives the ODPM aldehyde **64b** in low yield and the corresponding alkene resulting from decarbonylation. However, aldehyde **74**, in which there are no phenyl or vinyl groups to stabilize the biradical intermediates, does not undergo the ODPM rearrangement [20].

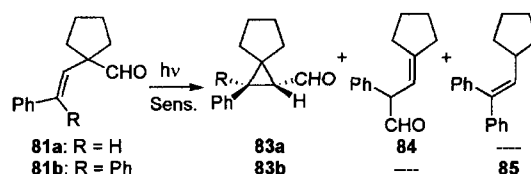
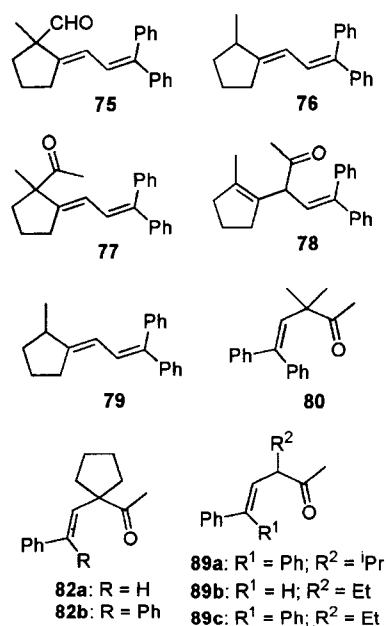
The above results have changed the ideas that most photochemists had for many years about the photoreactivity of β,γ -unsaturated aldehydes. From the work carried out mainly by Schaffner, Dürr and Pratt on the study of a series of compounds of this type a general consensus surrounding their lack of ODPM reactivity was originated [1,6]. Most of the compounds studied previously undergo decarbonylation, with only two exceptions. The decarbonylation takes place *via* either the S_1 ($^1n, \pi^*$) or T_2 ($^3n, \pi^*$) excited states. However, based on studies with analogous ketones the ODPM rearrangement of β,γ -unsaturated aldehydes almost surely occurs *via* the T_1 ($^3\pi, \pi^*$) excited state. The lack of ODPM reactivity of the aldehydes previously studied is probably due to the absence of the adequate substitution pattern that would allow efficient transfer of the triplet energy from the sensitizer to the alkene moiety. Therefore the T_1 ($^3\pi, \pi^*$) excited state, necessary for the ODPM rearrangement, would not be generated [20].

Based on our results, we proposed that β,γ -unsaturated aldehydes do indeed undergo efficient triplet ODPM rearrangement when the following criteria are met. First, the triplet energy of the sensitizer must be efficiently transferred to the C-C double bond in order to generate a T_1 ($^3\pi, \pi^*$) excited state of the substrate. Second, the biradical intermediates in the non-concerted ODPM pathway must be stabilized by conjugation with phenyl or vinyl groups. β,γ -Unsaturated aldehydes that do not meet these two requirements, like in most of the cases previously probed, undergo exclusive photodecarbonylation [20].

However, in a recent study [21] we have investigated the photoreactivity of aldehyde **75** that, according to the above postulates, presents a substitution pattern that should favor the ODPM rearrangement. Triplet-sensitized irradiation of **75** led to formation of diene **76**, the product of photo-decarbonylation, contrary to our expectations. No ODPM product was formed in this process. The formation of **76** is reminiscent of a Norrish Type I process. However, in this case, homolytic bond fission does not occur in the carbonyl $n\text{-}\pi^*$ excited state, as is the case in normal Norrish Type I reactions [3-5]. In addition, irradiation of the corresponding methyl ketone **77**, under the same conditions as used for **75**, afforded the product of 1,3-acyl migration, **78**. Again, no ODPM product was formed [21].

These results show that the well known Norrish Type I reactions of β,γ -unsaturated carbonyl compounds can take place by excitation of the alkene moiety rather than the carbonyl group. As far as we are aware, there are not examples in the literature of reactions of this type. The reason for this unusual reactivity may be that the T_1 (π,π^*) excited states of **75** and **77** possess sufficient energy to promote the homolytic bond fission at the allylic position to form the stabilized radical **79**. As a result photodecarbonylation competes favorably with the ODPM rearrangement

The surprising results obtained in the photoreactivity of compounds **75** and **77** have led to a modification of our preliminary conclusions on the factors that control the ODPM reactivity of β,γ -unsaturated aldehydes. Specifically, the observations indicate that in order to detect ODPM photoreactivity in β,γ -unsaturated aldehydes, substituents should be present to stabilize intermediate biradicals in the rearrangement pathway, but not to enhance alternative reactions, such as allylic homolytic cleavage [21].



Scheme 16.

A comparison of the photochemical reactivity of β,γ -unsaturated aldehydes and corresponding methyl ketones has shown that the ketones do not undergo the ODPM rearrangement while the corresponding aldehydes are reactive by this pathway [20,21]. These results contrast with firmly established, but apparently incorrect, ideas about the reactivity of compounds in these families [3-6]. Thus, for example, aldehyde **63b** undergoes the ODPM rearrangement whereas the corresponding methyl ketone **80** does not react in this manner [20]. Other examples of this situation have been found in the photochemical study of aldehydes **81a** and **81b**. Ketone **82a** has been reported unreactive in the ODPM mode [22]. However, triplet-sensitized irradiation of the corresponding aldehyde **81a** leads to generation of the spirocyclic derivative **83a**, as the *trans*-diastereoisomer, and **84**, a compound resulting from 1,3-formyl migration (Scheme 16). Irradiation of the diphenyl-analog **81b**, affords the ODPM product **83b** and the alkene **85** (Scheme 16). The formation of **85** might be due to the stabilization of the radical resulting from homolytic fission of the bond between the formyl group and the α -carbon, similarly to the reaction observed for compound **75**. In contrast the methyl ketone derivative **82b** does not undergo the ODPM rearrangement [21].

The results obtained in this comparative study support to the proposal that β,γ -unsaturated aldehydes are more prone to undergo the ODPM rearrangement than the corresponding methyl ketones, contrary to the opinion that many photochemists had on the photoreactivity of these compounds.

In an attempt to establish the limits for ODPM reactivity of β,γ -unsaturated aldehydes, the study was extended to a series of β,γ -unsaturated aldehydes **86**, which are monosubstituted at C-2 [21]. The literature precedents in the di- π -methane area have established that disubstitution at the central carbon of 1,4-diene acyclic substrates is an important structural requirement for the rearrangement [1-6]. In fact, there are only two examples in which acyclic β,γ -unsaturated ketones monosubstituted at α -position, undergo the ODPM reaction [22,23]. Therefore, it was considered of interest to explore the photoreactivity of compounds **86**. Triplet-sensitized irradiation of **86** leads to formation of the corresponding cyclopropanecarbaldehydes **87** (Scheme 17). The ODPM rearrangement of aldehydes **86** is stereoselective yielding only one diastereoisomer of **87**. The diphenyl-substituted aldehydes **86b** and **86d** yielded, in addition to the ODPM products, the corresponding alkenes **88a** and **88b**, resulting from photodecarbonylation. The

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