HETEROCYCLES, Vol. 60, No. 8, 2003, pp. 1921 - 1958
Received, 12th May, 2003, Accepted, 4th July, 2003, Published online, 15th July, 2003

PHOTOINDUCED ELECTRON TRANSFER REACTIONS IN HETEROCYCLIC CHEMISTRY

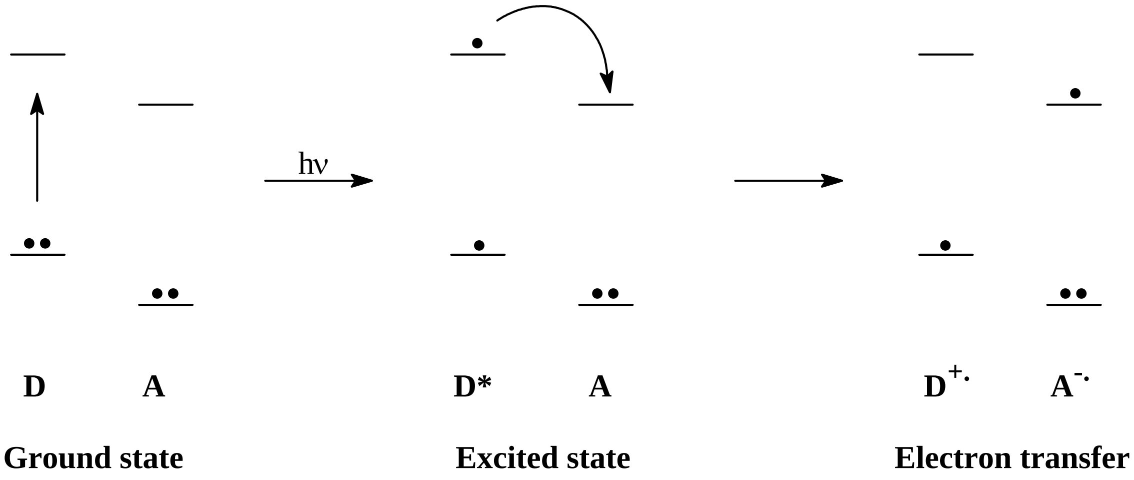
Maurizio Fagnoni
Department of Organic Chemistry, University of Pavia, Via Taramelli 10, 27100 Pavia, Italy
fagnoni@chifis.unipv.it

Abstract - In this work, the most significant reactions underwent by heterocyclic compounds under photoinduced electron transfer conditions have been reviewed, focusing the attention onto the possible applications of such reactions in organic synthesis and heterocycle functionalizations.

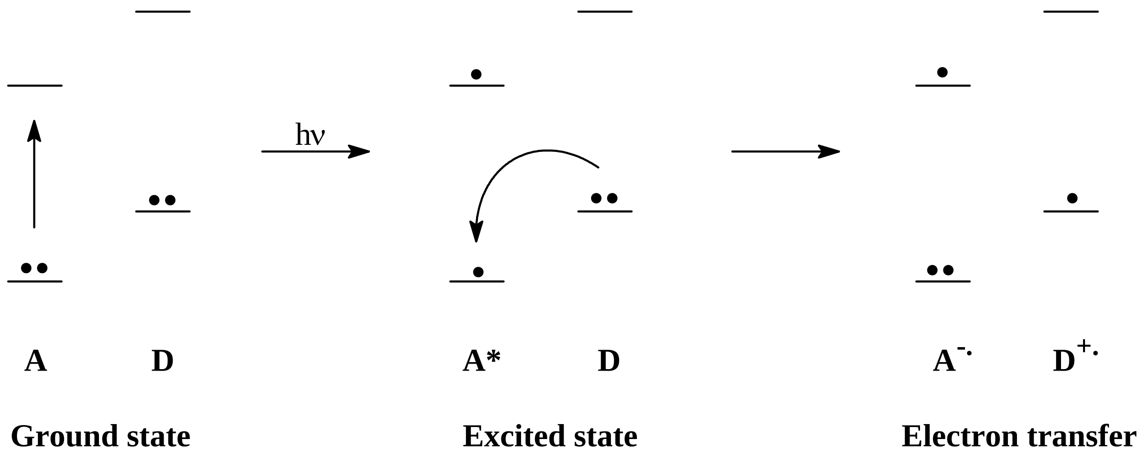
1. Introduction

Electron transfer processes (ET) involve the donation of an electron from a donor specie (D) to an acceptor (A). With organic compounds, ET reactions are quite common when the oxidation or the reduction step is initiated by an inorganic specie or by electrochemical means, while an ET process between two organic substrates is quite rare, at least among thermal reactions. However, excited states are both stronger oxidants and strong reductants than the corresponding ground states. In fact, the scenario changes dramatically when one of the two components is irradiated and an electron is promoted to a vacant orbital. As a consequence, the excited molecule can easily either donate this electron or accept one in the vacancy created in the formerly filled orbitals.[1] In the first case, excitation makes the light-absorbing molecule behave as a strong donor, in the latter one as a strong acceptor, as illustrated in the following Schemes 1 and 2.

Scheme 1



Scheme 2



In the ground state there is no way of having an efficient electron transfer, since the energy of the acceptor LUMO is too high. After the excitation of the donor, the excited state thus formed (D*) is able to donate an electron and a radical ions pair (the radical cation of the donor $D^{+\bullet}$ and the radical anion of the acceptor $A^{-\bullet}$) is formed.

Analogously, the excitation of the acceptor lead to the same radical ions pair.

Heteroaromatic compounds are ideal substrates for photoinduced electron transfer (PET) processes thanks to their strong absorptivity in the UV (in some cases also in the visible) region. Either $D^{+\bullet}$ or $A^{-\bullet}$ can be involved in chemical reactions which, in turn, can be divided in three main classes according to the role of the heteroaromatic. In the first case (eq *a*) the heteroaromatic is the donor and is oxidized by the excited state of a suitable sensitiser (the acceptor). Alternatively the radical cation (or the radical anion) of the heteroaromatic can be obtained from its excited state through electron transfer to the acceptor (or the donor) as depicted respectively in eq *b* and *c*.

a) $\text{Sensitiser} \longrightarrow \text{Sensitiser}^{*} + \text{Het(D)} \longrightarrow \text{Sensitiser}^{-\bullet} + \text{Het(D)}^{+\bullet} \longrightarrow \text{Reaction}$

b) $\text{Het(D)} \longrightarrow \text{Het(D)}^{*} + \text{A} \longrightarrow \text{Het(D)}^{+\bullet} + \text{A}^{-\bullet} \longrightarrow \text{Reaction}$

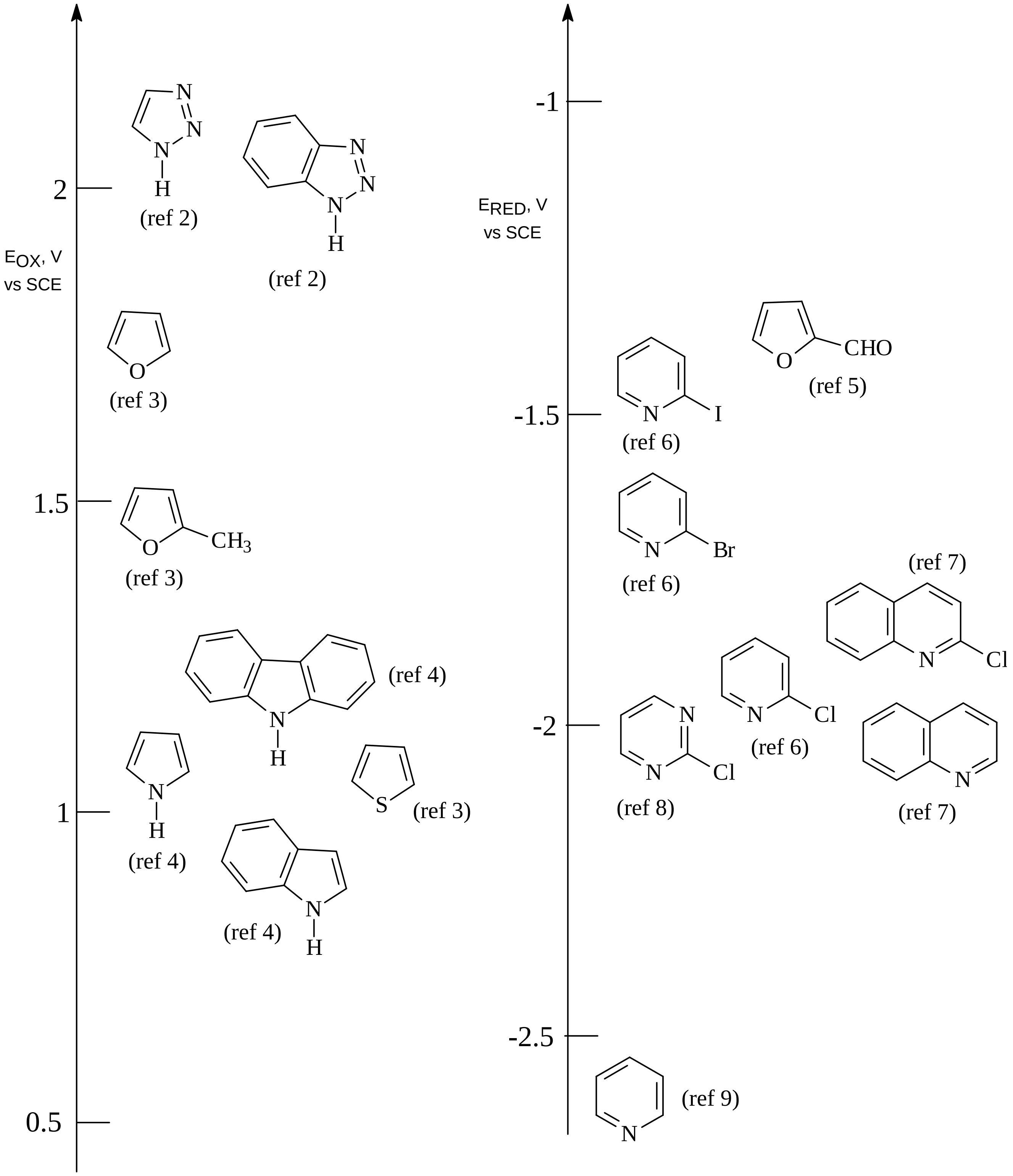
c) $\text{Het(A)} \longrightarrow \text{Het(A)}^{*} + \text{D} \longrightarrow \text{Het(A)}^{-\bullet} + \text{D}^{+\bullet} \longrightarrow \text{Reaction}$

Electron rich heterocycles viz. pyrrole, furans, thiophenes and indoles are suitable candidates for the role of donors and, on the contrary, electron poor pyridines, quinolines and acridines are good electron acceptors. The knowledge of oxidation potentials of the former ones and reduction potential of the latter ones is thus required for the evaluation of an electron transfer process as illustrated in Scheme 3. Heterocyclic derivatives that easily function as donors are listed according to their ground state oxidation potential, (Scheme 3, left part) and likewise in the right part heterocycles acting as acceptors are listed according to their reduction potential.

In Scheme 4 several sensitisers are also reported and are listed according to their reduction potential in the *excited state* (the higher is the potential the better is the oxidant capability). Among these, two examples of heteroaromatic sensitiser are found, viz pyrilium[10] and acridinium salts.[11]

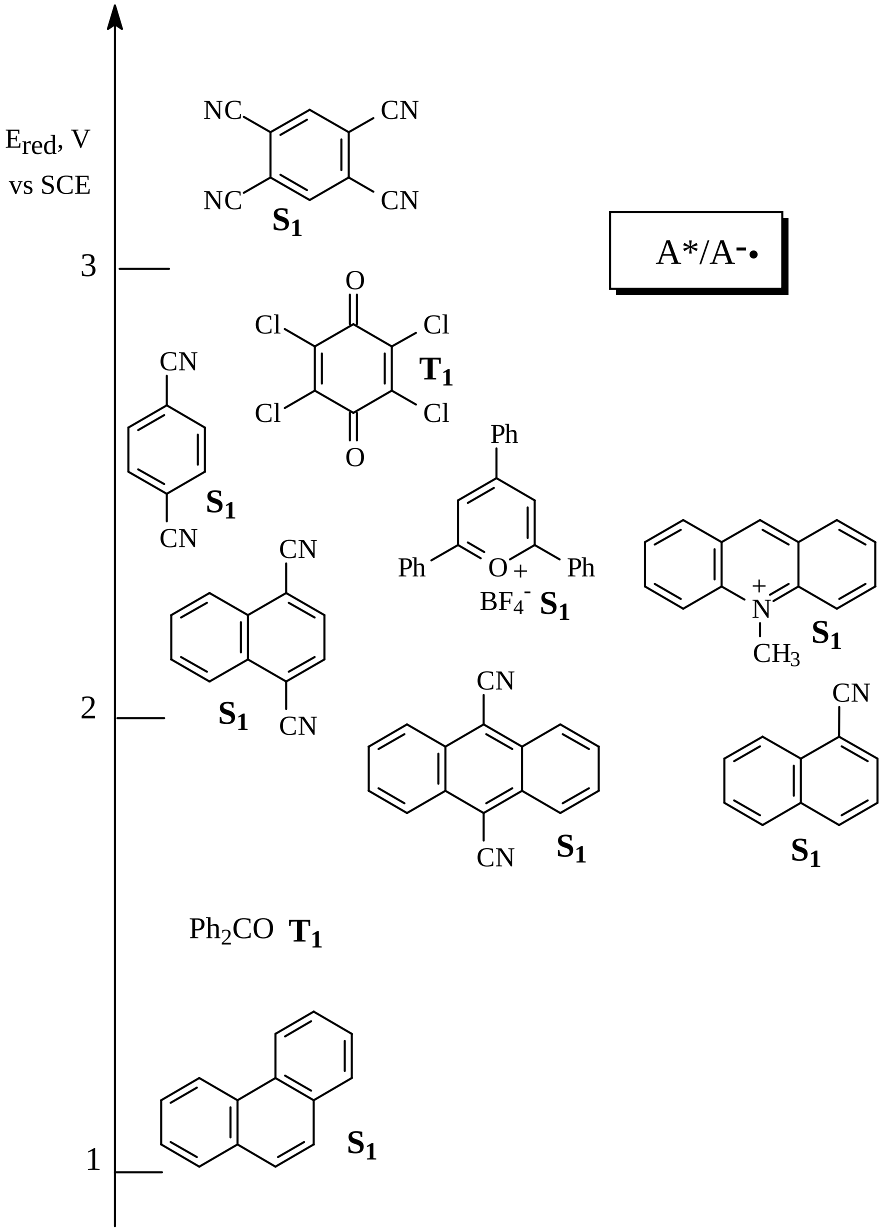
Application of PET reactions to heteroaromatics is a mild and useful alternative for their functionalization that might be appealing in view of the large importance that these derivatives have in the field of medicinal and agronomic chemistry. This review deals with reactions involving heteroaromatics (not their dihydro or in any way reduced derivatives[12]) under photoinduced electron transfer conditions. Reactions leading to the formation of heteroaromatic rings are likewise not discussed. General presentations of electron transfer reactions (thermal or photoinduced) for heterocycles are already available in the literature.[13]

Scheme 3



Therefore, this work considered only the PET reactions applied to heterocylic substrates with particular attention to the possible applications relevant from the synthetic point of view. The chapters have been prepared according to the reaction type, as indicated in the table of contents above.

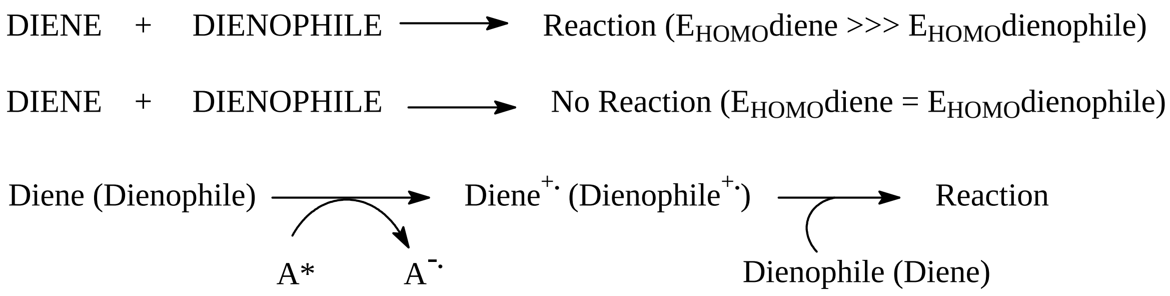
Scheme 4



2. Cycloaddition reactions

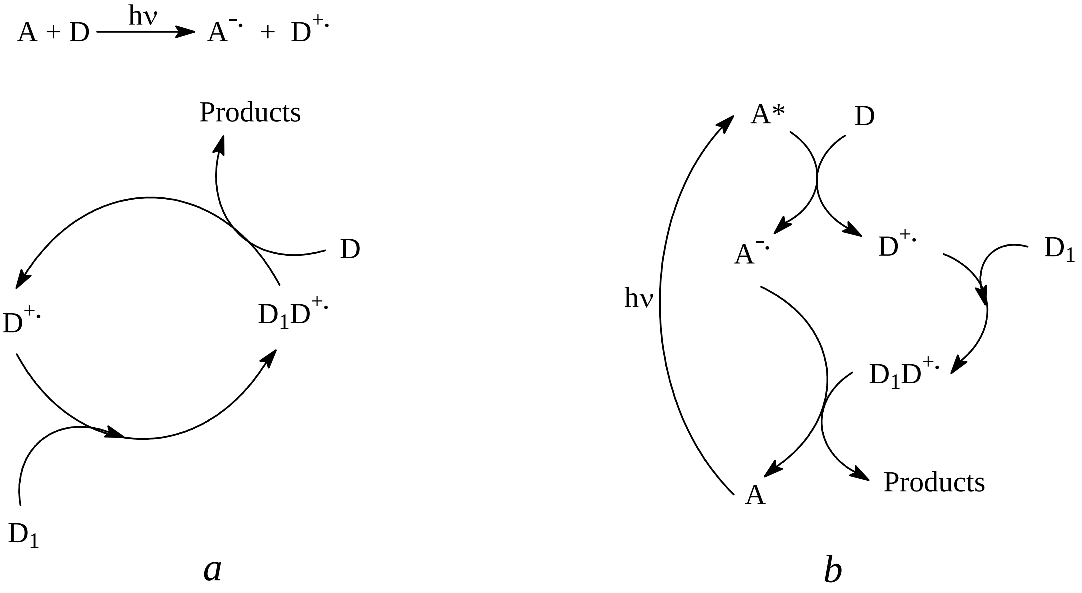
Cycloaddition reactions are one of the most largely employed methods for the construction of a ring.[14] In principle, [4+2] cycloaddition reactions occur between electron-rich dienes and electron-poor dienophiles (Diels-Alder reaction) or *vice versa* in the electron inverse demand version of the reaction. Because of this requirement, no cycloaddition takes place between two species having similar HOMO and LUMO energies. This limitation can be overcome by a preliminary PET oxidation of one of the two components. In such a way a radical cation is obtained and behaves as the electron-poor counterpart of the reaction. Cycloaddition thus occurs thanks to the redox *Umpolung* either of the 4π or the 2π partner of the reaction (substrate D in Scheme 5).[15] The rate increases several orders of magnitude with respect to the reaction of neutral dienes and dienophiles (D and D_1) due to a substantial lowering of the activation barrier for this path.

Scheme 5



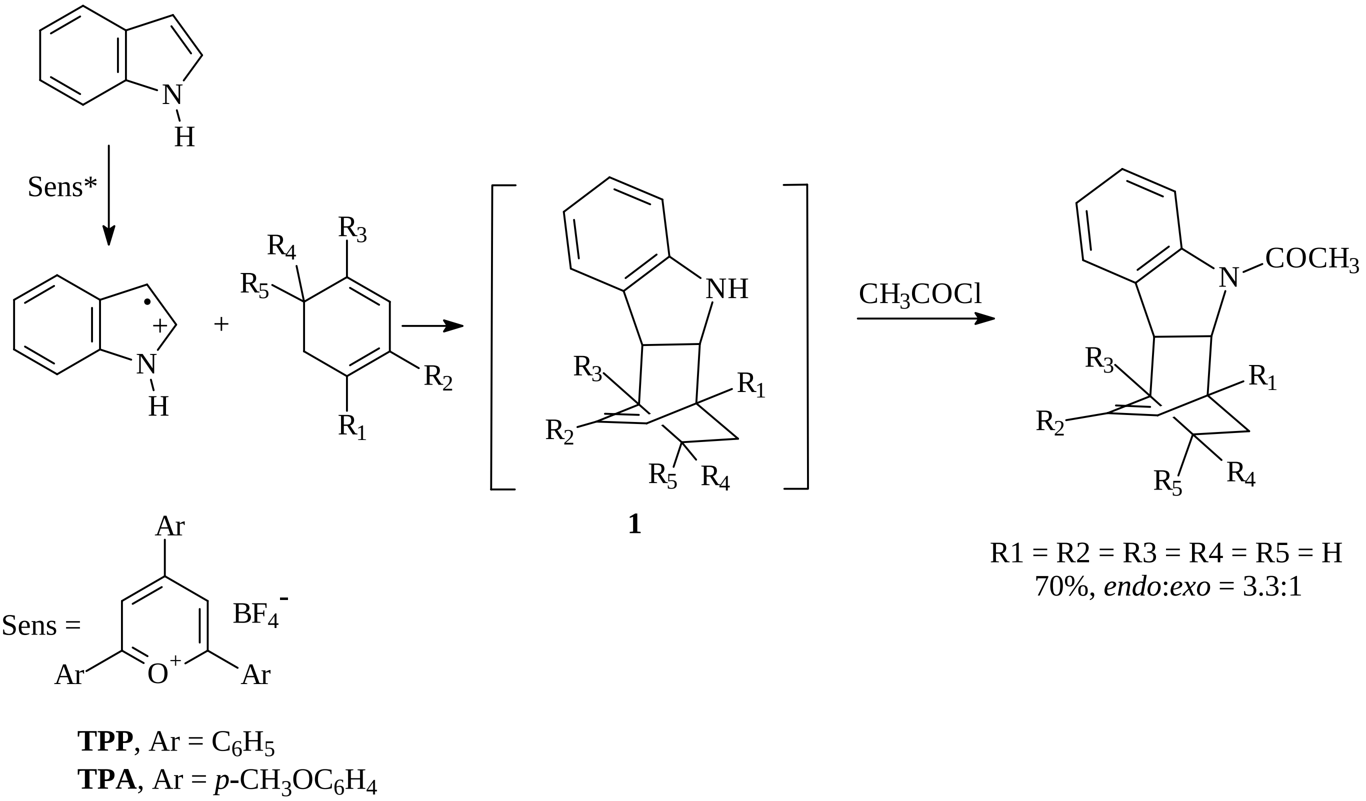
In order to explain the mechanism, two pathways were proposed. The first one (see Scheme 6, path *a*) was invoked to justify the high quantum yield values (Φ = 66) measured in some reactions and is based on the intervention of a chain process.[16] In the second one, appropriately designed as electron-transfer sensitisation, D is not involved in a chain reaction. The acceptor acts as the sensitiser and is regenerated during the course of the process; hence, it can be used in catalytic amount, at least in principle (path *b*).[16]

Scheme 6



Most of the [4 + 2] ET photosensitised cycloadditions reported in the literature result from the work by Steckhan on indole derivatives. Despite to the fact that the 2,3-double bond of these substrates is a good electron rich 2π addend, the usual thermal cycloaddition reactions have been limited to the reaction with electron-poor heterodienes in a acid catalysed fashion and under drastic conditions.[17] This limits the application of the reaction for the synthesis of complex indole derivatives having biologically activity. Monoelectronic oxidation of (substituted) indoles can be achieved photochemically in the presence of triphenylpyrylium salts; the radical cation thus formed reacts with the diene and a cycloadduct is formed (see Scheme 7).

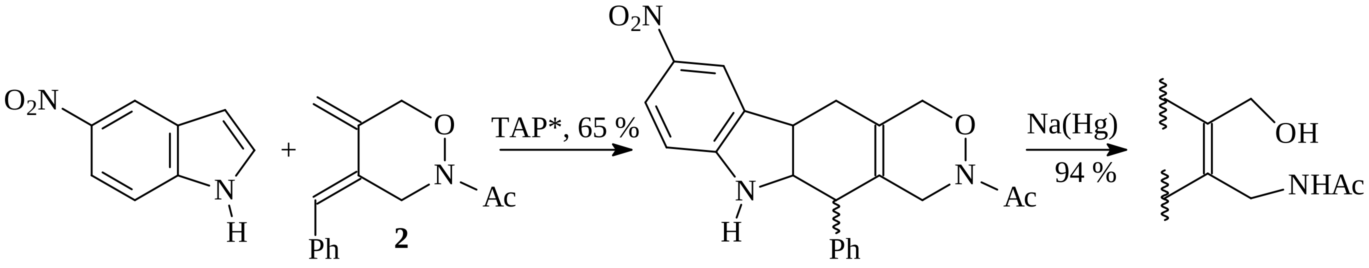
Scheme 7



In order to obtain satisfactory yields, the reaction was performed in the presence of acetyl chloride. This is because the non acetylated product (**1**) was easier to oxidize than the starting material and the further oxidation led to a complex mixture[18] (the same reaction carried out with methylindole in the absence of ArCl gave only a 10% yield of the adduct).

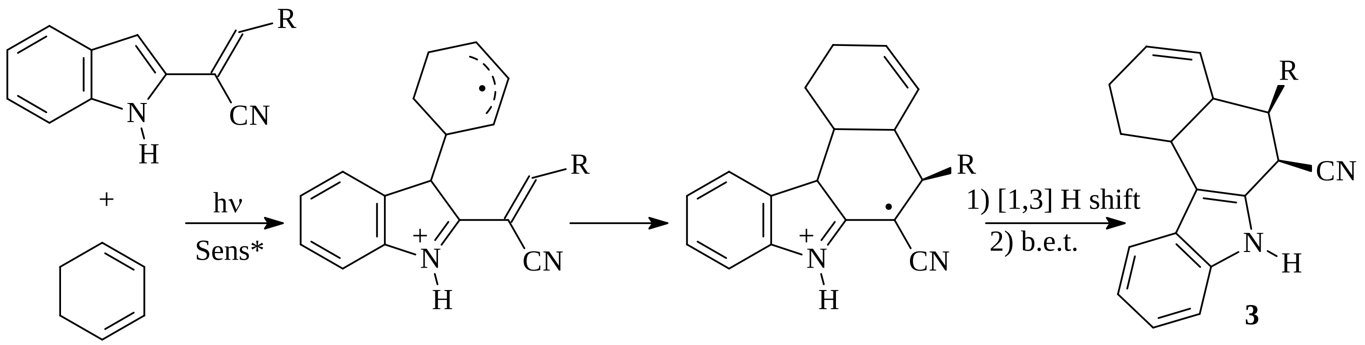
This reaction was proposed to follow path *b* in Scheme 6 with the initial formation of a ternary complex (a triplex[19]) between the donors and the acceptor. Calculations support a nonsynchronous-nonconcerted reaction, involving a relatively stable intermediate.[20] Such evidence can explain the complete regioselectivity observed, in which a substituent in the 1-position (2-position) of the cyclohexadiene moiety is found in the 1-position (3-position) of the carbazole product. Nevertheless, the reaction was inefficient when the indole carried a substituent on the 2,3- double bond (probably for steric reasons) and when open-chain dienes were employed (lack of a rigid *s-cis* conformation). As for the latter point, in order to broaden the synthetic scope of the reaction some exocyclic dienes incorporating an intentionally cleaving group were used. As an example, the reaction with (1,2)oxazinan-2-yl derivative (**2**) as the diene afforded the corresponding cycloadduct, which could be opened in a high yield through a reduction step.[21] (TAP = 2,4,6-tris(4-methoxyphenyl)pyrylium tetrafluoroborate, Scheme 8)

Scheme 8



Another class of suitable substrates for [4 + 2] cycloaddition reactions are 2-vinylindoles.[22] In this case the indole derivatives react as dienes and the course of the reaction is different. The first step is the oxidation of the indole with a subsequent addition onto cyclohexadiene. Cyclization followed by a [1,3] H shift and back electron transfer (bet) yielded carbazole (**3**). The use of chiral dienophiles led to a single isomer (Scheme 9).

Scheme 9



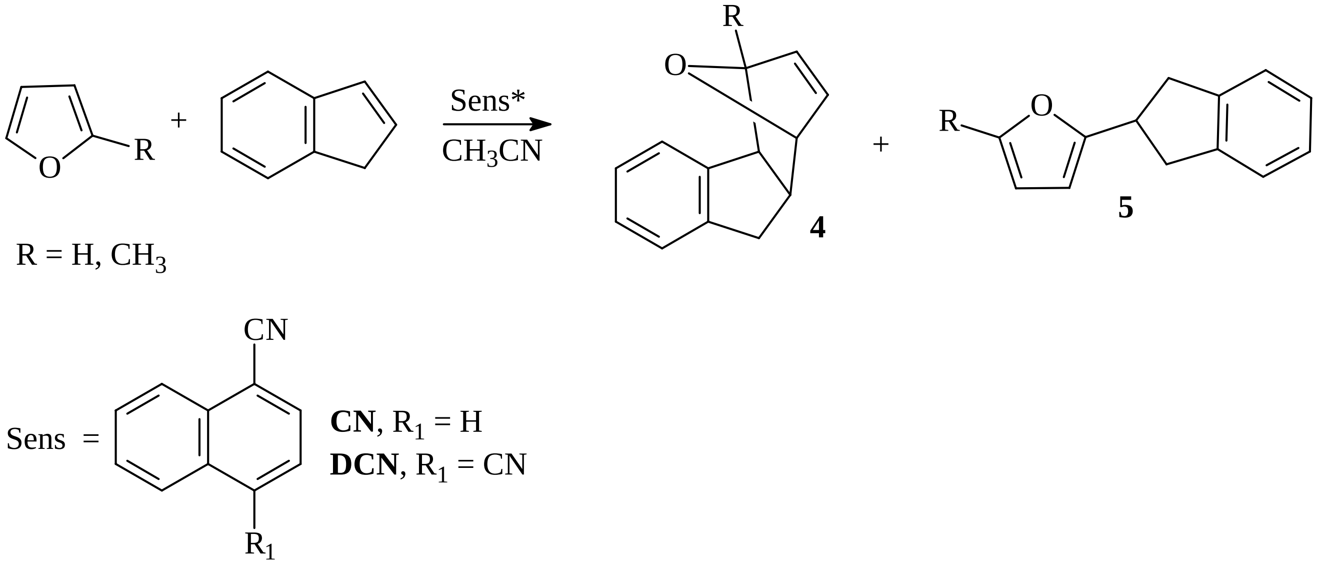
The reactions were successful only when the difference between the oxidation potentials of the two starting materials did not exceed 0.5 V.[22a]

As an example, substituted enamines are suitable dienes for this reaction, since they have exactly the same oxidation potential of the above mentioned vinylindoles.[23]

Similar reactions were carried out with 2-vinylbenzofurans, but unlike vinylindoles these compounds mainly reacted as dienophiles. The reaction with cyclohexadiene showed a predominant *endo*-selectivity.[24]

Furan behaves as a dienophile in the (di)cyanonaphthalene photosensitised reaction with indene.[25] The reaction formed two products, the photocycloadduct (**4**) and the substituted indene (**5**) (Scheme 10). The former product was the preferred one only if there were no substituent on the furan ring; the presence of a methyl group in the 2 position dramatically enhanced the yield of the substitution product.[25]

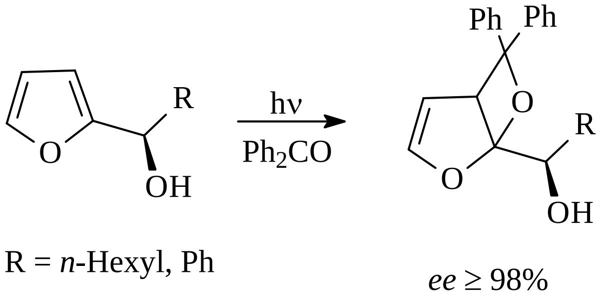
Scheme 10



2.1. Paternò-Buchi

The Paternò-Buchi reaction, i. e. the [2+2] cycloaddition between an excited carbonyl compound and an alkene leading to the synthesis of oxetanes, is one of the most important photochemical reactions. The mechanism involves a diradicalic intermediate but in particular cases exciplex or electron-transfer pathways were invoked.[26] Only recently, a few examples using heterocycles were reported as described in the photocycloaddition reaction between furylmethanols and aromatic ketones (Scheme 11). ET activation explained the regiochemistry of such reactions, particularly when benzophenone was used as acceptor.[27]

Scheme 11

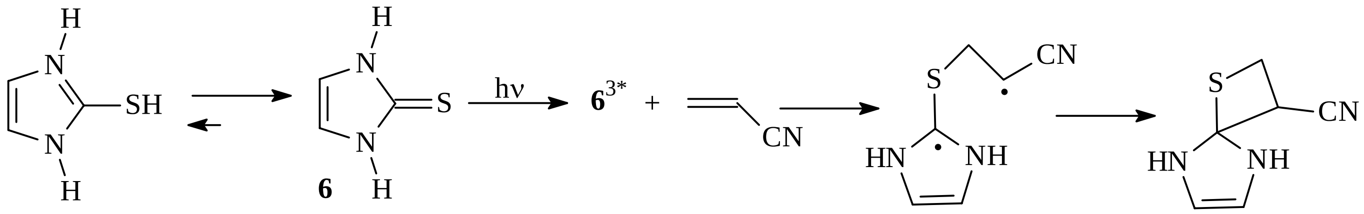


The reaction showed a high degree of regioselectivity (addition onto the more substituted double bond) and with a chiral substrate, also a high stereoselectivity.

Cycloaddition on the carbonyl moiety of 1-acetylisatin occurred from the contact ion-radical pair only with electron-rich alkenes such as diphenylethylene derivatives.[28]

The triplet state of 1,3-dihydroimidazole-2-thiones (**6**) was readily quenched by good electron acceptors such as dinitrobenzenes, leading to the radical ion pairs. A partial charge-transfer character was also invoked in the reaction with electron-poor alkenes where a [2+2] cycloadduct was observed (Scheme 12).[29]

Scheme 12



6

3. $S_{RN}1$ reactions

An important class of substitution reactions are those occurring by $S_{RN}1$ mechanism;[30] these substitutions have been extended by Bunnet to (hetero)aromatic compounds in the early seventies[31] and are often more efficient when photostimulated. Such reactions were in part reviewed elsewhere; [30,13b] thus, only a selection of examples is reported here.

The mechanism of the reaction is depicted in Scheme 13.

Scheme 13

Photochemical initiation step

$$\mathrm{HetX} + \mathrm{Nu}^- \xrightarrow{h\nu} \mathrm{HetX}^{-\bullet} + \mathrm{Nu}^\bullet \qquad (1)$$

Chain propagation

$$\mathrm{HetX}^{-\bullet} \longrightarrow \mathrm{Het}^\bullet + \mathrm{X}^- \qquad (2)$$

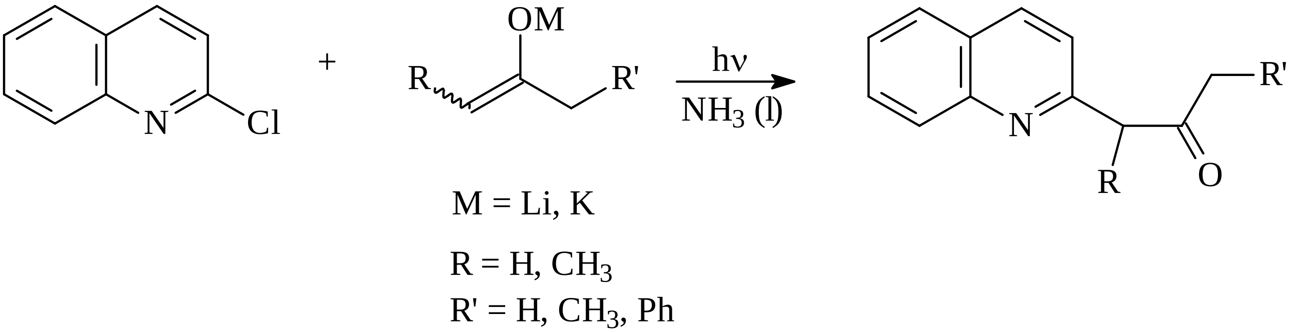
$$\mathrm{Het}^\bullet + \mathrm{Nu}^- \longrightarrow \mathrm{HetNu}^{-\bullet} \qquad (3)$$

$$\mathrm{HetNu}^{-\bullet} + \mathrm{HetX} \longrightarrow \mathrm{HetNu} + \mathrm{HetX}^{-\bullet} \qquad (4)$$

The first step of the reaction is the photostimulated electron transfer between an (hetero)aromatic halide and a negatively charged nucleophile (eq. 1). The (hetero)aromatic radical anion thus formed fragments beginning the propagation of the chain. As a result, the alkylation of the (hetero)aromatic (HetNu) occurs with the concomitant regeneration of the radical anion of the starting (hetero)arene, which starts a new cycle.

Most of these reactions have been carried out in liquid ammonia using enolate anions as nucleophiles and halides (usually bromides or chlorides) as nucleofugal group X^-. The order of reactivity was usually correlated with the bond strenght of the C-X bond, thus the weaker was this bond the higher was the reactivity. The overall reactivity followed the order: iodides> bromides> chlorides. Nitrogen containing six-membered heterocycles (pyridines, quinolines, pyrazines, pyrimidines and pyridazines) had been mainly employed in $S_{RN}1$ reactions. A representative example was the photoalkylation of 2-chloroquinoline with lithioacetone. The reaction worked to some extent in the dark but in the presence of UV light the reaction rate increased dramatically (Scheme 14).[32] It should be noted that substitution yields were largely affected by enolate concentration and that β-dicarbonyl enolates were reluctant to react under this conditions.[32]

Scheme 14



M = Li, K

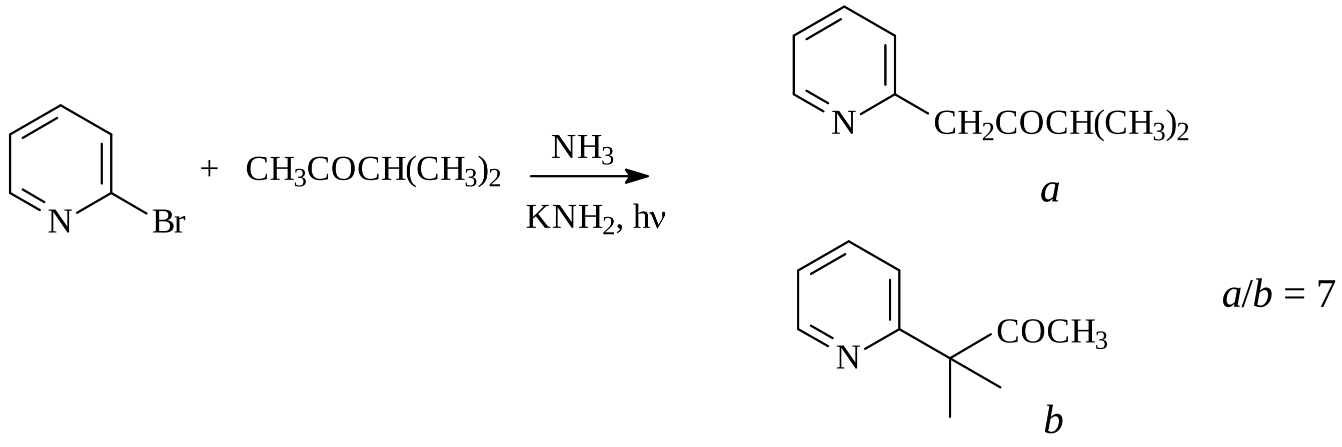
R = H, CH_3
R' = H, CH_3, Ph

Mono- and polyhalopyridines likewise underwent efficient $S_{RN}1$ reactions as has been reported by Wolfe.[33] The crucial step of the reaction was identified in the rate of carbon-halogen cleavage of the heteroaromatic radical anion intermediate. This was shown to depend on the free electron density at the carbon bearing the halogen, the strength of that bonds and the redox potential of the substrate-radical anion couple.[33b] When the starting ketone can lead to two different enolates, a mixture of the two possible isomers is usually obtained, with a preference for the kinetically controlled one (Scheme 15).[33a]

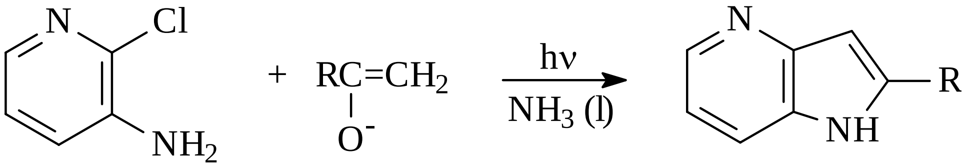
The presence of an amino group adjacent to the halogen as in the case of 2-chloro-3-aminopyridines is exploited for building a pyrrole fused ring (Scheme 16).[34]

Polyhalogenated heteroaromatics led usually to complete substitution even under short irradiation time and when different halogens were present probably due to the fast dehalogenation of the monoalkylated radical anion intermediate (Scheme 17).[13b]

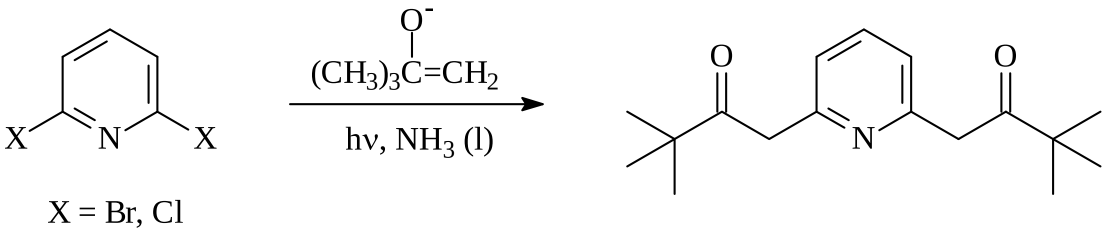
Scheme 15



Scheme 16



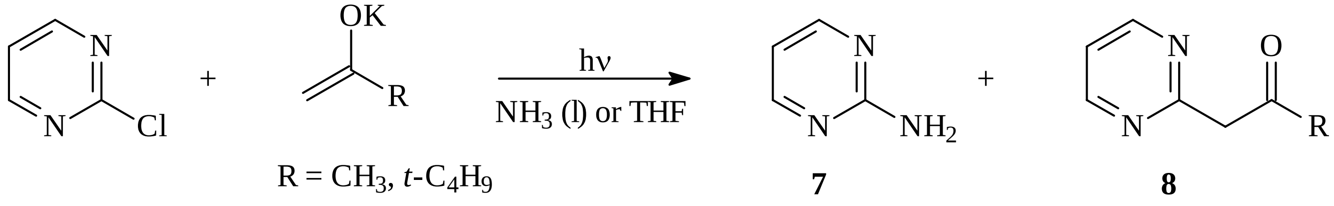
Scheme 17



Liquid ammonia seemed not to be the best solvent in the alkylation of halogenopyrimidines. In the case of 2-chloropyrimidines[35a] the reaction with lithiopinacolone in ammonia as the solvent occurred in a modest yield (32%); traces of amino derivatives (**7**, 4%) along with other unidentified products were also observed. On the contrary, the reaction with lithioacetone gave product (**8**) in 61% yield only when changing the reaction medium to THF (Scheme 18); furthermore, the yield of compound (**7**) increased from 4 to 88% yield when passing from irradiated to non irradiated conditions.

The alkylation of 5-chloropyrimidine derivatives was likewise reported, though it occurred in a modest yield, due to competing reaction pathways.[35b]

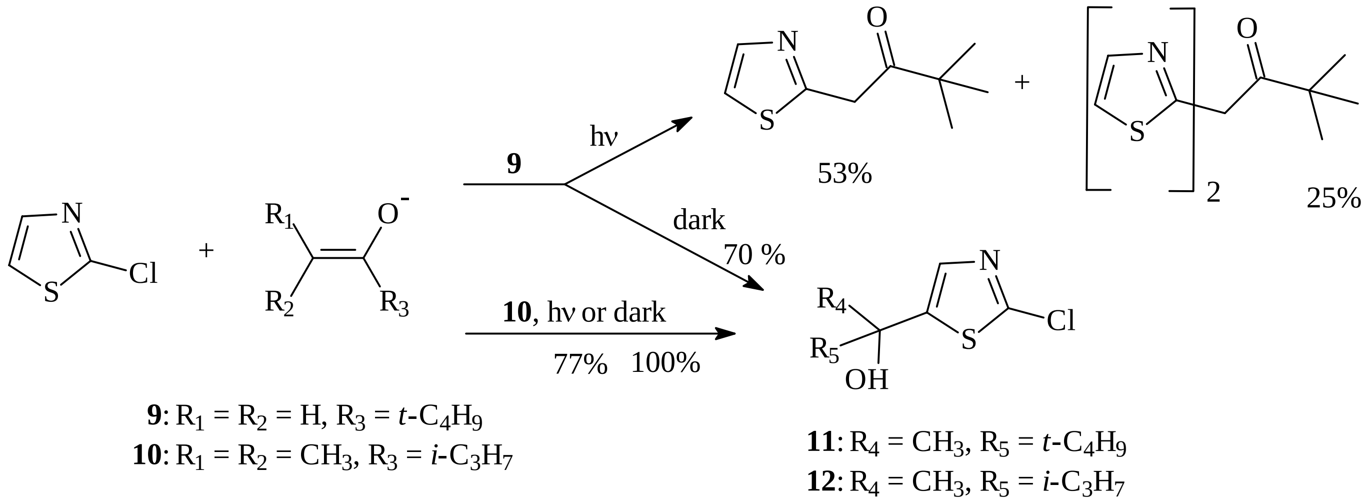
Scheme 18



The irradiation step was also crucial with chloropyridazines[35a] but surprisingly the isomeric chloropyrazines reacted even in the dark. This behavior was attributed to the less negative E_{RED} value of the latter compounds, which caused a faster electron transfer initiation of the process.

Sulfur containing heterocycles showed a peculiar behavior with respect to the $S_{RN}1$ process. The reaction of 2-chlorothiazole in the presence of enolates gave different products according to the enolate used (Scheme 19).[36] The usual photostimulated $S_{RN}1$ process took place with pinacolone enolates, though a significant amount of biaryl derivative was obtained. The same reaction performed in the dark afforded carbinol (**11**).

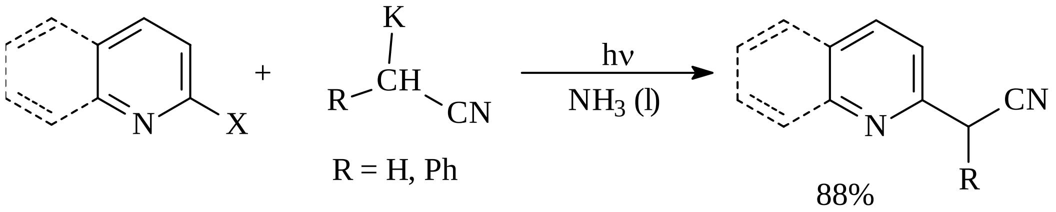
Scheme 19



A carbinol was formed also in the reaction with **10**, both in the presence and in the absence of photostimulation. As for the latter product, Authors suggested that partial deprotonation of H5 of the thiazole ring by the enolates followed by reaction with the ketone was responsible of this competing pathway. The difference observed in the reactivity could be explained by the fact that diisopropyl ketone enolate is a less effective initiator of the $S_{RN}1$ process than pinacolone. Modest yields were also observed in the alkylation of the 3-halo-2-amino derivatives of benzo[*b*]thiophene;[37] the unsatisfactory result was due to the competition by the reduction of the substrate.

Some $S_{RN}1$ reactions using the iminates prepared from nitriles gave yields comparable with those previously described with the enolates. Halopyridines and -quinolines were alkylated in very high yield especially when the negative charge was stabilized by an adjacent phenyl group[38] (Scheme 20).

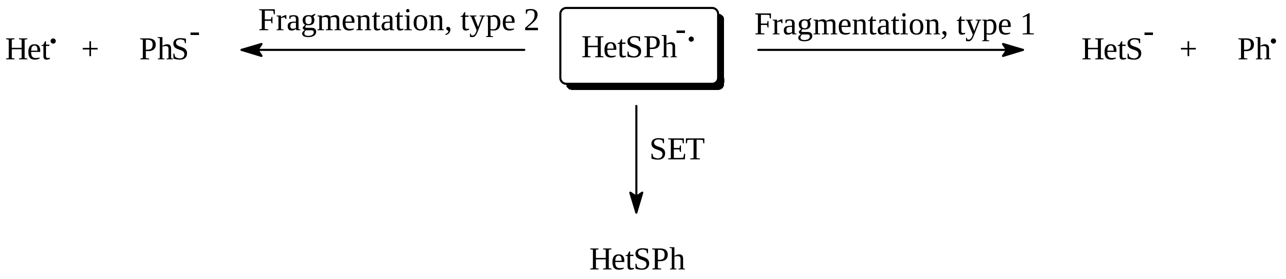
Scheme 20



Photostimulated reactions in the presence of potassium acetonitrile occurred in a lesser yield and some byproducts were detected.[38] On the contrary, irradiation was detrimental in the substitution of halothiophene by α-cyano substituted carbanions because of the light induced degradation of the final products; as a consequence, this reaction was better performed in the dark.[36]

Thiolate anions are another class of reagents used,[38,39] but the success of the reaction is strictly related to the fate of the useful radical anion intermediate. (Scheme 21)

Scheme 21



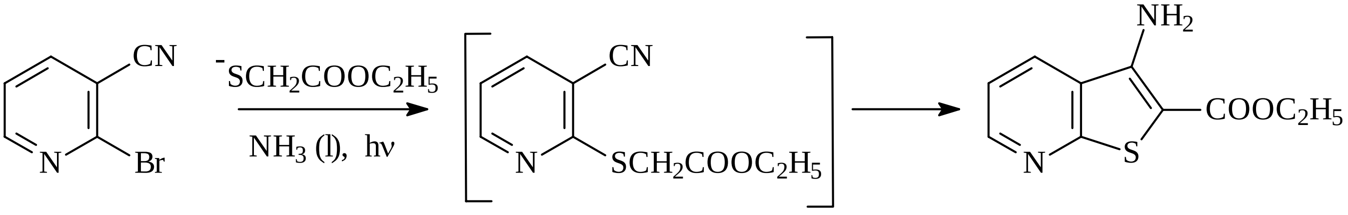
In fact, such intermediates underwent three competing reactions. The first path led to the usual substitution product *via* a SET process but two different fragmentations competed at this level. Both pathways involved a fragmentation to give a thiolate anion, either through S-Ph or Het-S bond cleavage. The ratio of the products obtained depended mainly on the changes in the rate of fragmentation and not on a change in the electron-transfer reaction.[39b]

Improvement in the yields of substitution products could be achieved through the addition of suitable electron acceptors (EA) such as PhCN or $PhNO_2$. In this case, efficient electron transfer precluded the fragmentation pathways. (eq 5).[39a]

$$\mathrm{HetSPh}^{-\bullet} + \mathrm{EA} \rightleftharpoons \mathrm{HetSPh} + \mathrm{EA}^{-\bullet} \qquad (5)$$

An interesting application of thiolates was the synthesis of thienopyridines starting from bromocyanopyridines[40] (Scheme 22) through cyclization of the intermediate (**13**).

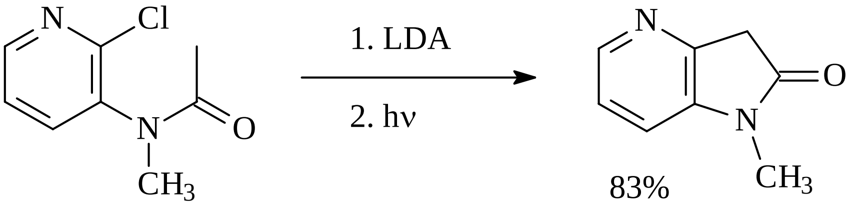
Scheme 22



13

Despite the versatility of the reaction, only a few intramolecular $S_{RN}1$ reactions have been reported. As an example 2-chloro-3-(*N*-methylacetamido)pyridine underwent photocyclisation to an azaoxindole[41] (Scheme 23).

Scheme 23



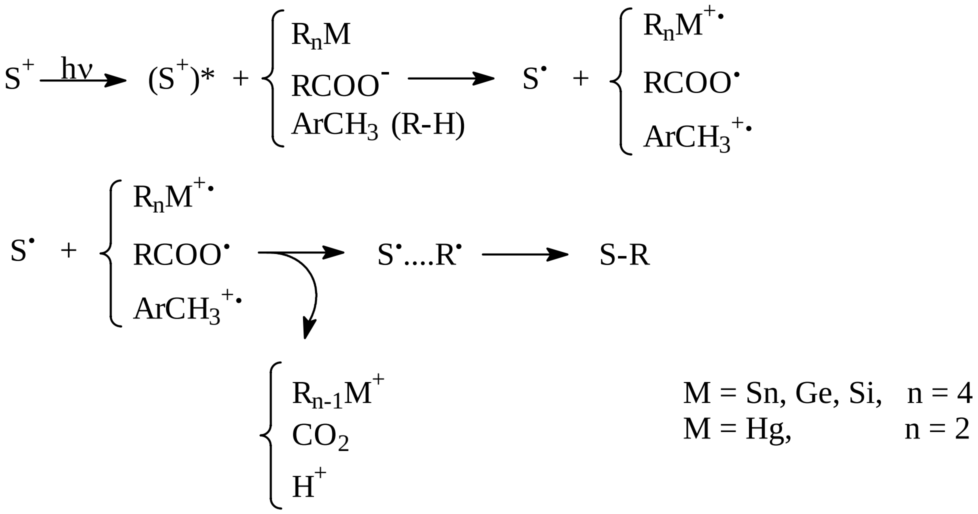
4. Reductive addition

Several electron transfer heteroaromatic photosensiters (S) are positively charged and thus give a neutral radical upon accepting an electron in their excited state from a donor. On the other hand, donors like tetralkylstannanes, -germanes or -silanes (in general derivatives of group 14 elements, R_4M) or dialkylmercury compounds, when oxidized form radical cations. These readily fragment generating alkyl radicals. Radical- radical coupling between such intermediates and the reduced sensitiser yields addition products. An analogous path is followed when the donors are the salts of carboxylic acids ($RCOO^-$) or methylbenzenes. In the last two cases, radicals are formed by carbon dioxide loss or by depronation respectively. Reductive addition pathways are depicted in the following scheme (S = sensitiser, Scheme 24):

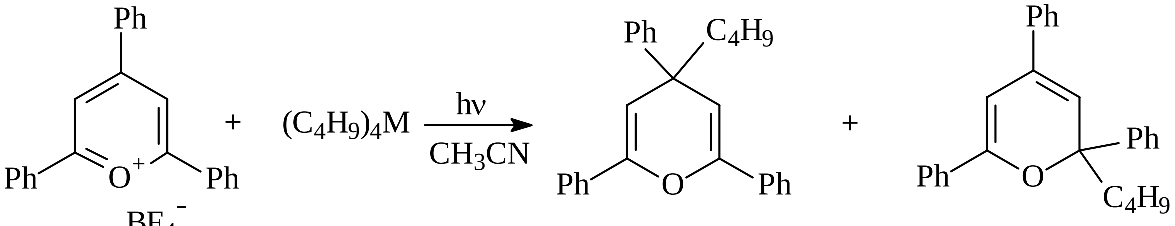
Pyrylium salts were easily alkylated in acetonitrile when irradiated in the presence of tetrabutyl metallorganic compounds (**14-16**)[42a] and the overall yield paralleled the oxidation potential of the donors; stannanes have the highest potential in the series, followed by germanes and silanes. 2- And 4-

triphenyldihydropyranes were obtained as the end products with a slight preference for the 2 isomer (Scheme 25).

Scheme 24



Scheme 25

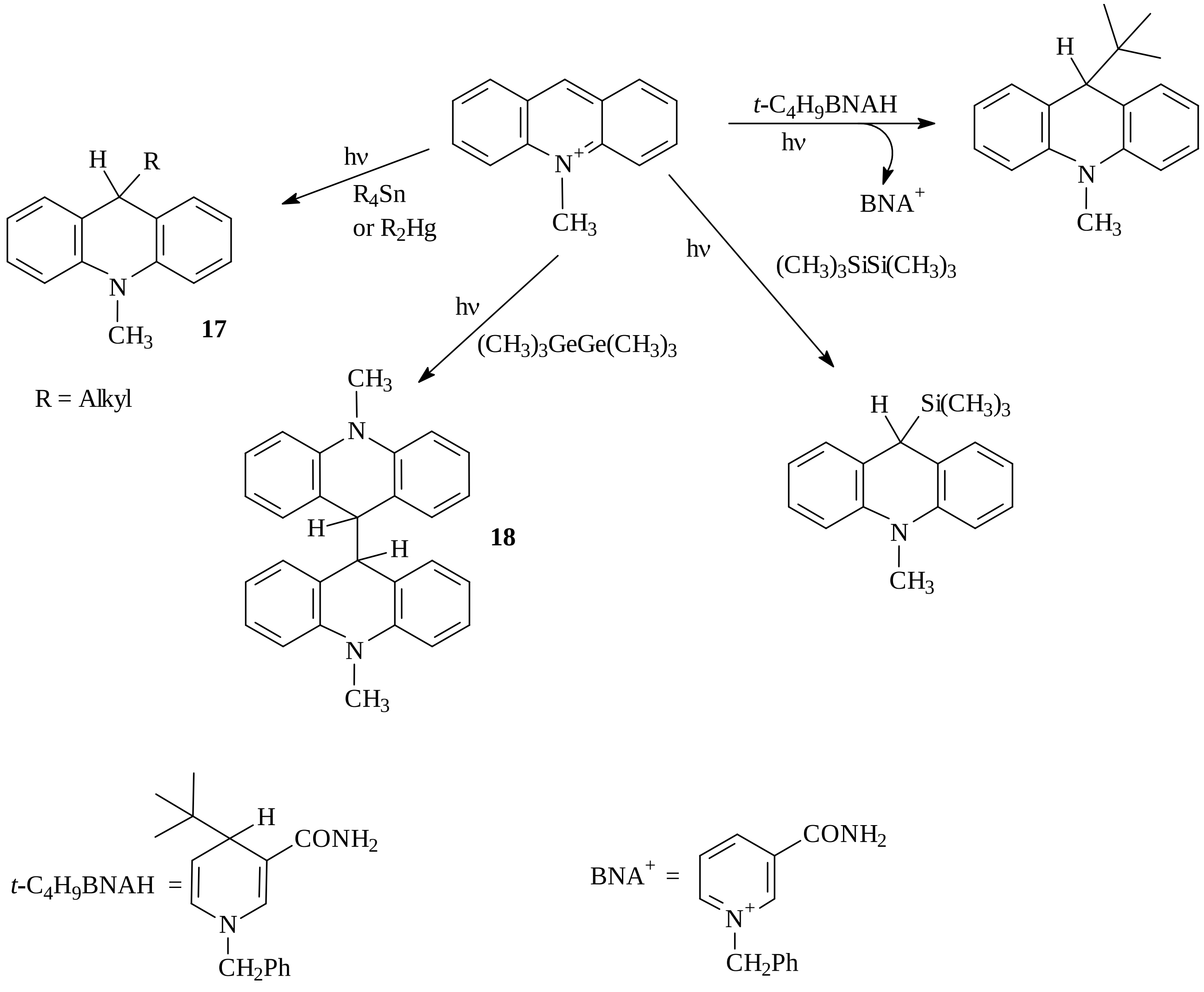


14:	M = Sn	58%	31%
15:	M = Ge	16%	6%
16:	M = Si	5%	trace

Thanks to their high reactivity, stannanes were largely employed in the functionalization of several sensitisers. The alkylation of various 2,6-diaryl(dialkyl)pyrylium salts were studied both from the mechanistic and from the synthetic point of view. Under appropriate conditions, alkylation only in position 4 was observed. Alkylated pyrylium salts were isolated due to the easy oxidation of the dihydro intermediates.[42b]

Acridinium salts underwent a similar addition reaction, with the advantage of the complete regioselectivity of the attack (the addition occurred only in position 9).[43] The alkylation products depended on the donor used; with tetraalkylstannanes,[44a] dialkylmercury[44a] and carboxylic acids,[44b] 9-alkyl-10-methylacridanes (**17**) were obtained (Scheme 26). The same reaction was applied for allylation or benzylation reactions.[45] Silylation was likewise obtained when Me_6Si_2 was used as a donor via attack of the intermediate $Me_3Si^{\cdot}$ radical.[46a] Surprisingly, no organometallic derivatives were observed with hexamethylgermane where the acridinium radical intermediate dimerized yielding compound (**18**).[46b] (Scheme 26). Recent studies have demonstrated that this reaction can be performed successfully also in a nonpolar solvent and the toxic organometallic radical precursor can be replaced by using 4-alkyl-1-benzyl-1,4-dihydronicotinamide (RBNAH) derivatives.[46c]

Scheme 26

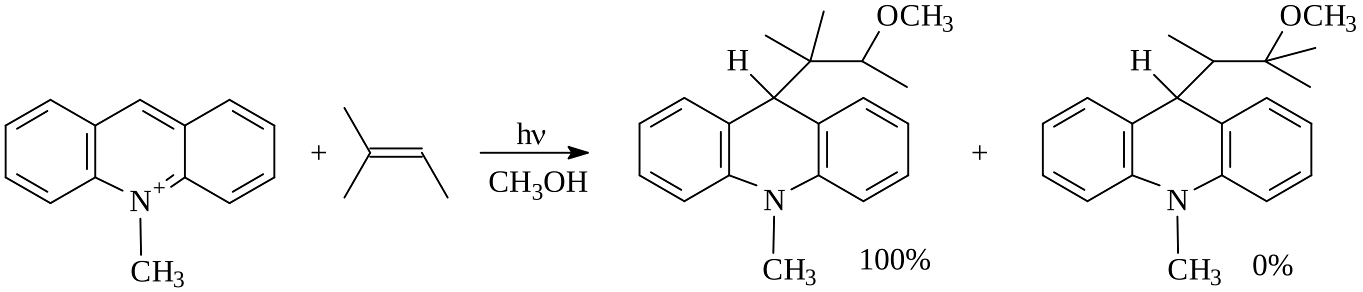


Another photochemical reaction of heteroaromatic iminium salts is the alkylation by hexabutyldistannane of quinolinium salts. With the salt of 4-methylquinoline as the substrate, a 2-butyl derivative was isolated.[47] In the presence of *t*-butyl bromide, a significant amount of 2-*t*-butyllepidine was also formed in the reaction due to the competitive generation of the *t*-butyl radical from the halide by abstraction by the

$(C_4H_9)_3Sn^{\cdot}$ radical. The latter radical was supposed to be formed by photoinduced homolytic fragmentation of the starting hexabutyldistannane.[47]

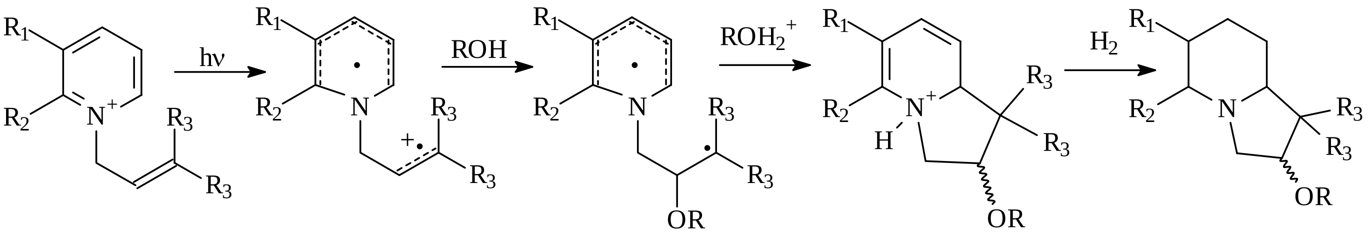
Substituted alkenes or alcohols are suitable donors for the synthesis of building block of natural compounds particularly when electron transfer is intramolecular. As an example, Scheme 27 illustrates the reaction of an acridinium sensitiser with alkenes in the presence of a nucleophilic solvent such as CH_3OH. The first step was the formation of the alkene radical cation. The subsequent reaction with the reduced sensitiser was in turn followed by nucleophilic addition of the solvent in an anti-Markovnikoff way.[48] Mechanistic studies demonstrated that CH_3OH addition occurred at least in part in a concerted manner.

Scheme 27



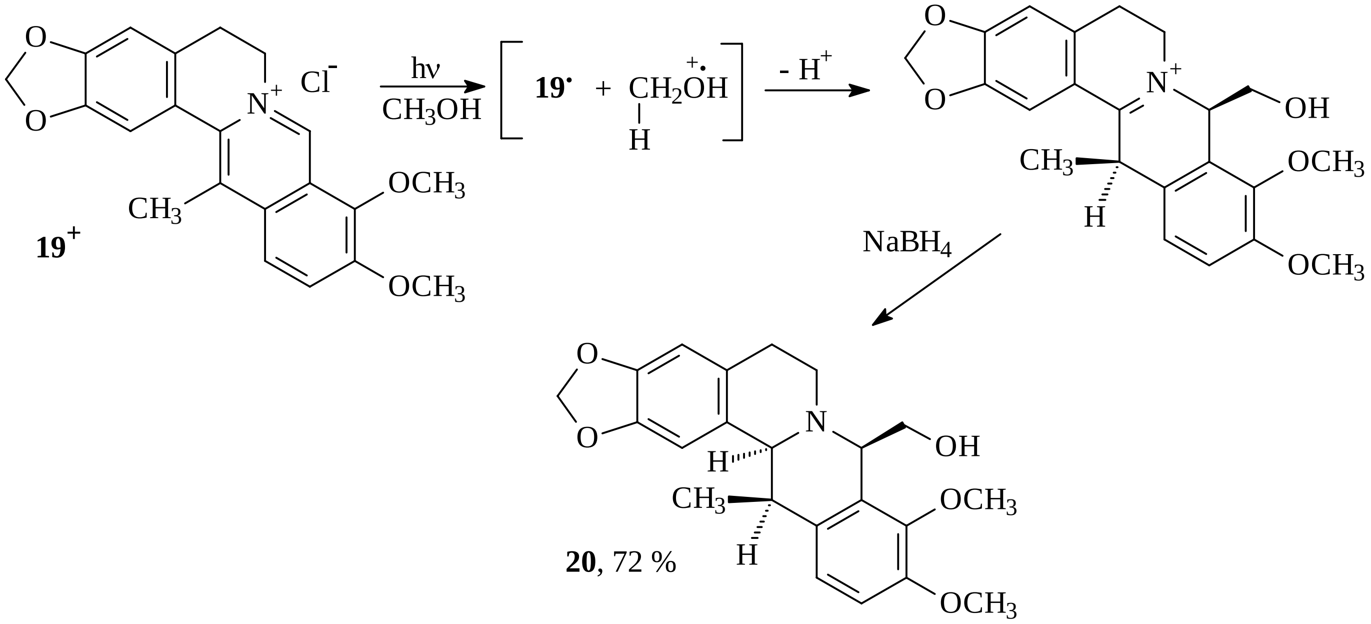
N-Allylpyridinium substrates were suitable precursors for the synthesis of indolizidines.[49] The intramolecular electron transfer reaction between the iminium moiety and the double bond was again followed by nucleophilic attack by the solvent and cyclization. Hydrogenation of the crude photolysate was found to be the best way for isolating the final product avoiding degradation (Scheme 28).

Scheme 28



Irradiation of 13-methylberberine chloride (**19**$^+$) in CH_3OH yielded (±)-13-hydroxymethylthalictricavine (**20**) in a high yield and with complete stereoselectivity. This was attributed by authors to the radical coupling step, due to the pseudoequatorial position adopted by the C-8 methyl group (Scheme 29).[50]

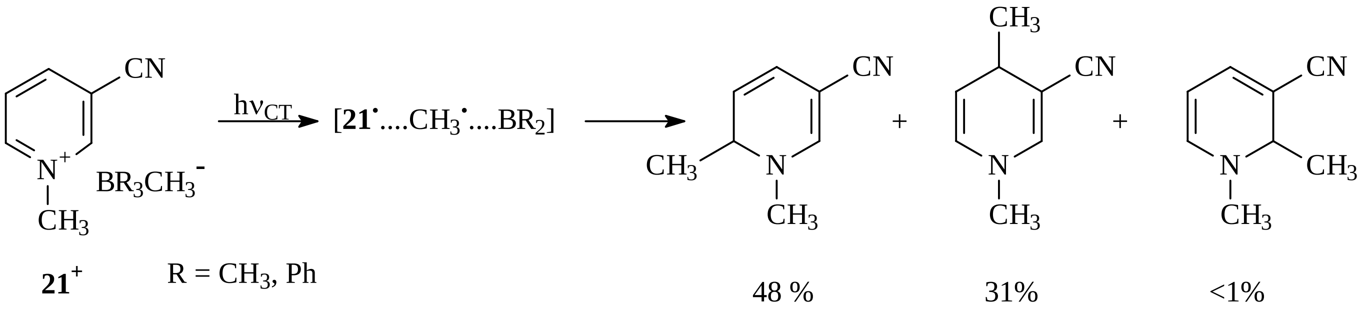
Scheme 29



Acridinium salts substituted in position 9 with an enediyne system tethered to a guaiacol were synthesized as a model for testing the induction of single and double strand DNA cleavage. Irradiation of this model compound caused an intramolecular electron transfer with the formation of a highly conjugated biradical.[51]

Methylation of various positively charged *N*-heterocycles (e. g. **21**) was again achieved by irradiation of the charge transfer complex formed with tetramethyl(methyltriphenyl)borate counterions (Scheme 30).[52]

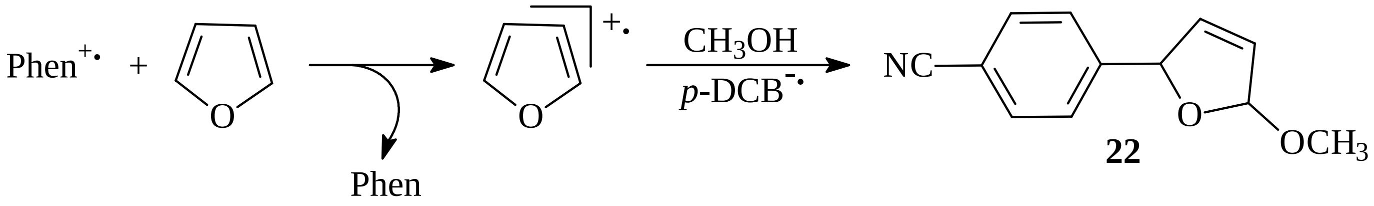
Scheme 30



In some cases, reductive addition reactions involved neutral heteroaromatics. Irradiation of an acetonitrile-methanol solution containing *p*-dicyanobenzene (*p*-DCB) and furan in the presence of a secondary donor such as phenanthrene (Phen) led to the formation of dihydrofuran derivatives (**22**) (Scheme 31).[53]

Scheme 31

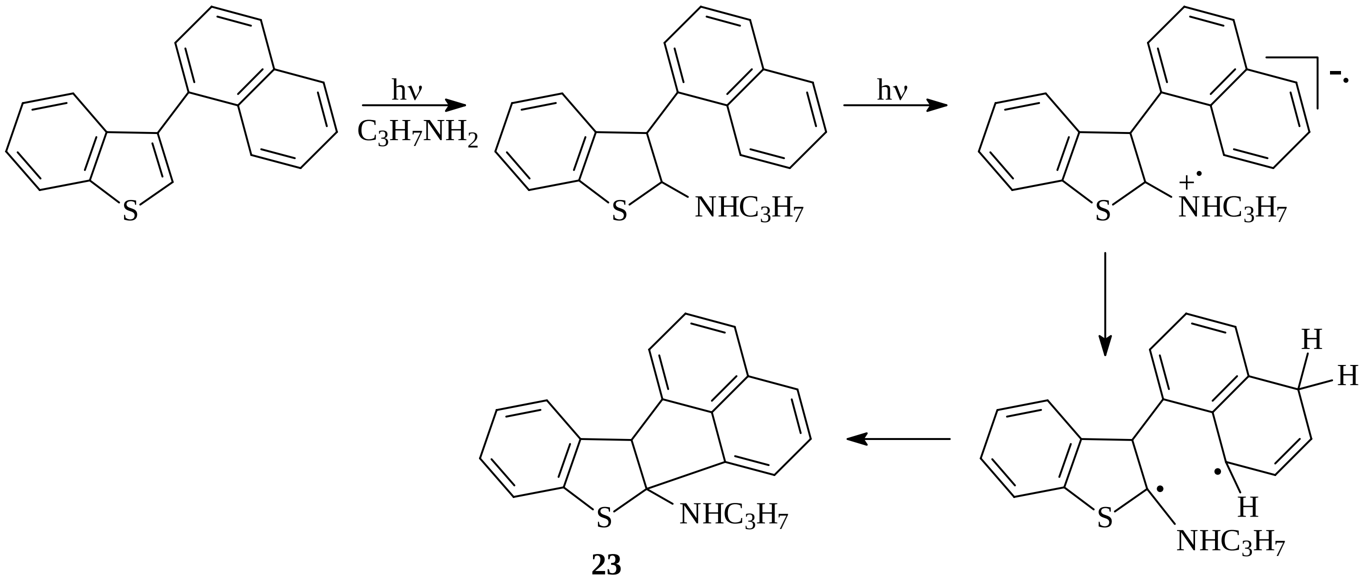
$$\mathrm{Phen}^{1*} + p\text{-DCB} \longrightarrow \mathrm{Phen}^{+\bullet} + p\text{-DCB}^{-\bullet}$$



PET reactions between benzo[*b*]thiophene and secondary amines gave 2,3-dihydrobenzo[*b*]thiophen-3-yl-dialkylamines through radical coupling between *N*-aryl radicals generated from deprotonation of the amine radical cation and the thiophene radical anion.[54]

A two photons reaction was responsible of the conversion of 3-naphthylbenzo[*b*]thiophene into the pentacyclic derivatives (**23**) (see Scheme 32). The first step was photoaddition of propylamine and was followed by intramolecular electron and proton transfer and subsequent cyclization.[55]

Scheme 32



The tetranitromethane radical anion was a convenient source of $NO_2^{\cdot}$ radicals and $(O_2N)_3C^-$ anion; as an example, the addition of both species onto benzofuran was quite efficient, though rather unselective, leading preferentially to 3-nitro-2-trinitromethyl-2,3-dihydrofurans upon photoinduced electron transfer to tetranitromethane.[56]

5. Substitution reaction

Another well documented class of ET photoinduced reactions of heteroaromatics involves photosubstitution reactions. It is convenient to divide such reactions into three different classes, according to the group that is substituted in the reaction, viz. hydrogen, a halogen or a cyano group. In the first case the heterocycle is the donor (Het-H) and the acceptor is an alkyl or arylhalides AX (in some cases, the solvent itself). After the PET step a halide anion is liberated upon fragmentation of the radical anion and the products are formed by radical-radical cation coupling and proton loss (Scheme 33). In both of the last classes, the heteroaromatic (Het-Y) is the acceptor, whereas the donor is usually an arene or an amine. The mechanism is analogous to the previous case and in order to favour the process a good electrofugal group such as the trimethylsilyl group may be present in the donor structure.

Scheme 33

H substitution

$$\text{Het-H (donor)} + \text{AX} \xrightarrow{h\nu} \text{Het-H}^{+\bullet} + \text{AX}^{-\bullet} \xrightarrow{-\text{X}^-} \text{Het-H}^{+\bullet} + \text{A}^{\bullet} \xrightarrow{-\text{H}^+} \boxed{\text{Products}}$$

X = Cl, Br, I

Halogen or cyano substitution

$$\text{Het-Y (acceptor)} + \text{DW} \longrightarrow \text{Het-Y}^{-\bullet} + \text{DW}^{+\bullet} \xrightarrow{-\text{Y}^-} \text{Het}^{\bullet} + \text{DW}^{+\bullet} \xrightarrow{-\text{W}^+} \boxed{\text{Products}}$$

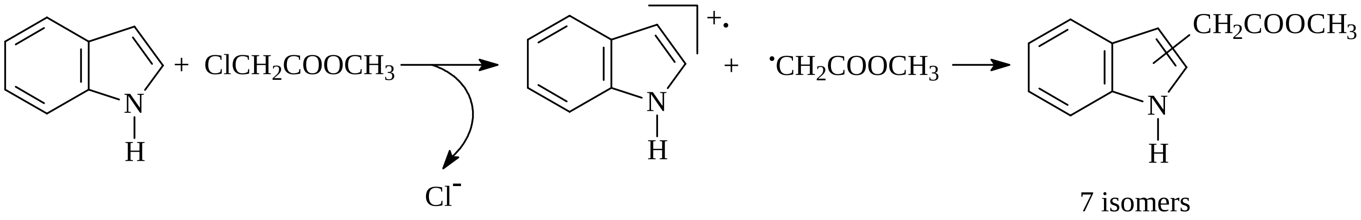
Y = Cl, Br, I, CN; W = H, $Si(CH_3)_3$

5.1 Substitution of a hydrogen

Various reactions type belong to this class. Pyrrole derivatives were alkylated in the photoreaction with π nucleophiles such as stilbene[57] or naphthalene,[58] yielding respectively 1,2-diphenylethyl- and dihydronaphtylpyrroles. In both cases a marked preference for α-substitution on the pyrole ring was observed. Selectivity was complete in the alkylation of 2-methylfuran with 1,1-diphenylethylene, in which 5-(2,2-diphenylethyl)-2-methylfuran was isolated in 87% yield.[3] With electron poor olefins the reaction worked as well, but electron transfer was involved only at the exciplex level. Thus, indole was cyanoethylated by reaction with acrylonitrile.[59]

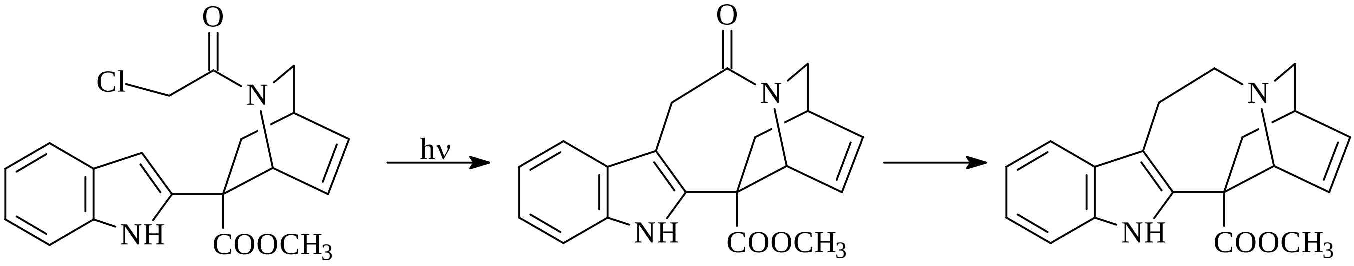
PET oxidation of heteroaromatics in the presence of various halides led to formation of a C-C bond *via* halide anion loss from the radical anion intermediate and subsequent radical-radical cation coupling. Unfortunately, in most cases these reactions lacked in selectivity, as illustrated in the alkylation of indole in the presence of chloro ethyl acetate, where each one of the seven possible positions was alkylated (Scheme 34).[60]

Scheme 34



When the last reaction was carried out in an intramolecular version with indoles bearing the chloroacetamide moiety tethered in an appropriate position, interesting indole alkaloid precursors could be obtained.[61] In such a way, 20-deethylcatharanthine (**24**) was obtained after cyclization onto the C3 position of the indole skeleton (Scheme 35).[62]

Scheme 35



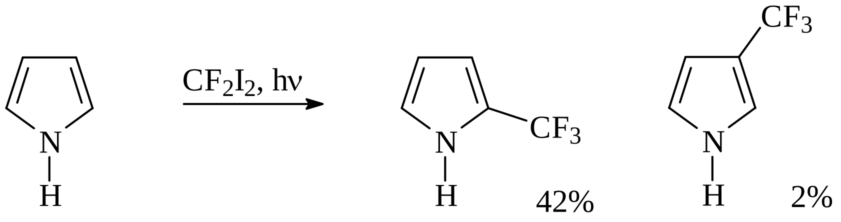
24

This cyclization mode was typical for all indoles bearing the chloroacetamide moiety in position 2, while such a high regioselectivity was difficult to obtain in similar system where the electron accepting moiety was tethered to different indole positions. Several examples of such reactions were reported in the literature.[63] A similar cyclization was finally reported on a modified tryptophan but, unlike the other cases, a chloroallyl moiety was then the reducible part of the molecule.[64]

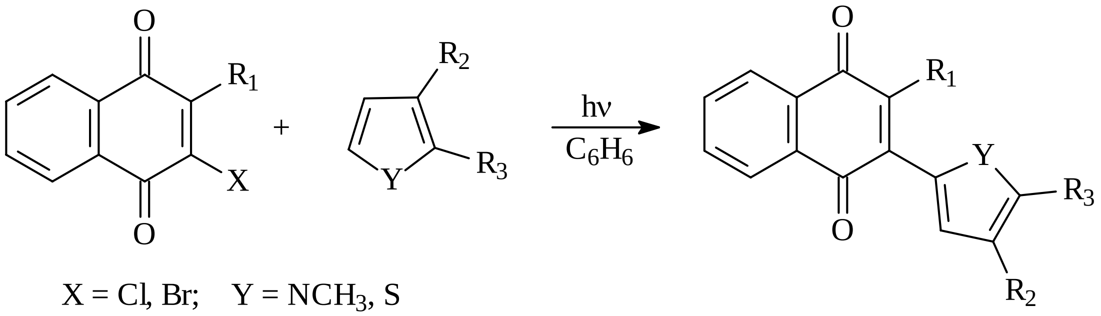
Chloroform and CCl_4 were tipycal examples of easily reducible solvents for the addition of $^{\bullet}CCl_3$ or $^{\bullet}CHCl_2$ radicals onto heterocycles radical cations obtained either from carbazoles[65] or from benzothiazoles.[66] Trifluoromethylation was explored starting from difluorodiiodomethane; yields were modest and the final products were obtained through the difluoroiodomethyl intermediates (Scheme 36).[67]

Reactions were cleaner when halo-1,4-naphthoquinones were used as electron acceptors. The regioselectivity of the process attracted much attention for a photochemical synthesis of dyes of this class, as an alternative to the thermal counterpart (Scheme 37).[68]

Scheme 36



Scheme 37

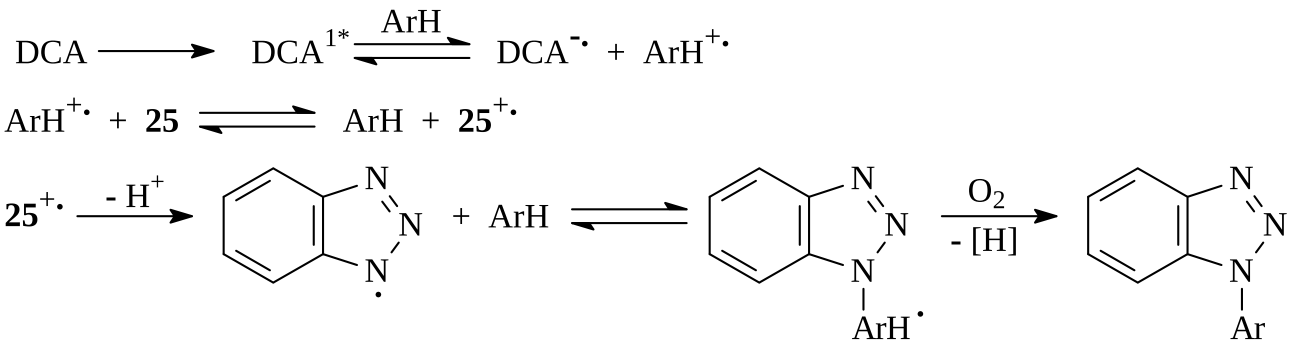


Electron transfer is also an appropriate method for generating particular radicals otherwise difficult to obtain. As an example, the pentafluorophenylation of heteroaromatics has been achieved starting either from pentafluorophenyl iodide[69a] or sulfonates *via* PET. [69b]

As mentioned in Section 4, irradiation of benzofuran in the presence of tetranitromethane leads to reductive addition of both fragments. However, shifting the reaction medium from dichloromethane to hexafluoroisopropanol changed the outcome. Thus, nitration of 2,8-dimethylbenzofuran gave the 3-nitro substitution adduct as the major product with an overall yield > 90 %.[70]

There is a single example of ring arylation of a heteroatom. This is illustrated in Scheme 38 and involved benzotriazole (**25**). The electron transfer step was induced by the presence of a secondary electron acceptor (dicyanoanthracene, DCA) as the absorbing specie. The aromatic substrate ArH underwent attack by the benzotriazolyl radical formed. [71] The formyl function of thiophene-2-carbaldehyde was reduced through a PET process by indole and the thus initiated reaction led to diindolylmethane derivatives after the reaction of a second molecule of the donor with the electrophilic alkylideneindolenine intermediate.[72]

Scheme 38



N-Containing heterocycles (pyridines, quinolines and their corresponding iminium salts) were also alkylated (in some cases in a high yield and with a good stereoselectivity) by alkyl radicals photogenerated from alkylmercurials.[73a] The reaction mainly gave substitution products even if reduced derivatives could be the main products according to the structure of the starting heterocycles or reaction conditions (the presence of PTSA and KI in the reaction medium and *N*-methylated heterocycles as the substrates favor the latter process).[73b]

Substitution of a hydrogen by a cyano group was achieved in the PET oxidation of *N*-alkyl(aryl)pyrroles by the *p*-dicyanobenzene excited state in the presence of sodium cyanide. The reaction was regioselective, with the exclusive formation of α-cyanopyrroles. A similar behavior was observed when the reaction was carried out under anodic oxidation conditions.[74]

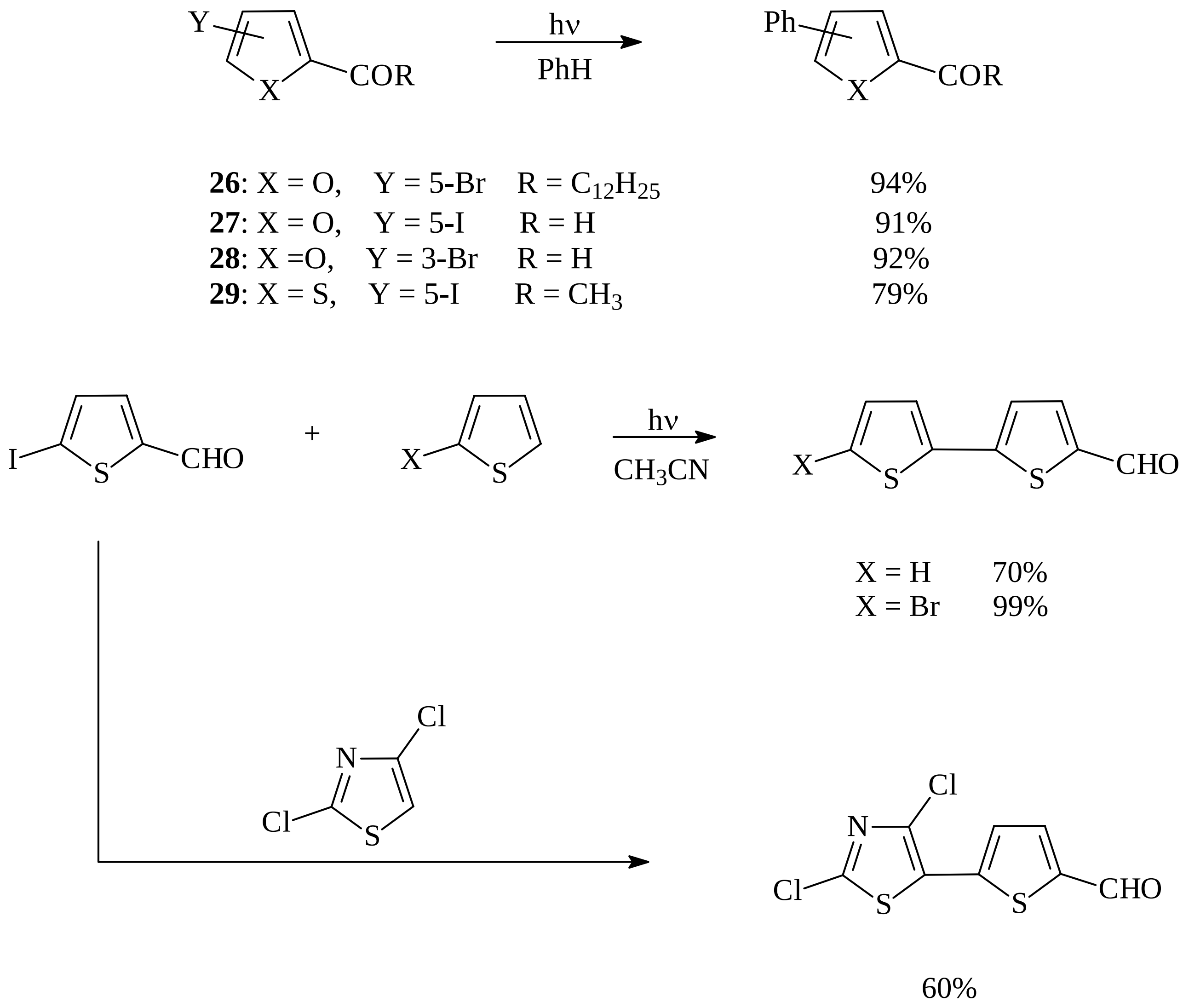
5.2 Substitution of a halogen

Several contributes to this field arise from the work of D'Auria's group. In this frame, bromo- or iodo-furans or thiophenes substituted with an aldehyde or a ketone function underwent efficient photochemical arylation or alkylation. Some examples are shown in Scheme 39. Irradiation of **26-29** in the presence of benzene or other easily oxidized heteroaromatics gave rise to an exciplex. The next step was radical ions coupling with elimination of HY.[75] This reaction scheme was used succesfully for the synthesis of naturally occurring bithiophenes.[76]

5;5'-Diformyl-2,2'-difuran was obtained in the same way from furfural and 5-bromo-2-furfural, in a reaction which is a convenient alternative to the classical Ulmann reaction and to Pd-catalysed coupling methods.[77]

The presence of a vinyl or an ethynyl group on the aromatic ring of the donor induced a different course of the reaction. The formation of an aryl-aryl bond was superseded by aryl-vinyl(ethynyl) bond, thus affording an expeditious synthesis of products (**30**) and (**31**) (Scheme 40).[78]

Scheme 39



26: X = O, Y = 5-Br R = $C_{12}H_{25}$ 94%
27: X = O, Y = 5-I R = H 91%
28: X =O, Y = 3-Br R = H 92%
29: X = S, Y = 5-I R = CH_3 79%

X = H 70%
X = Br 99%

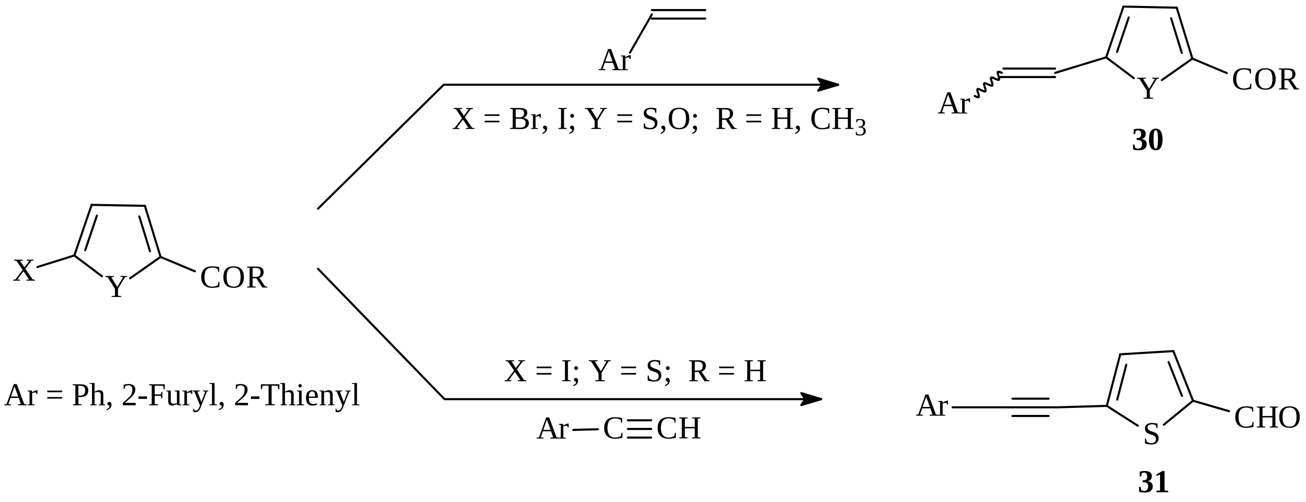
60%

Quinone analogue molecules, such as 5-bromo-1,3-dimethyluracil (**32**) and 5-bromouridine were investigated in the photoreaction with tryptophan derivatives, in connection with the study of the cross-linking of nucleic acid and proteins.[79] As for the latter point, it should be noticed that the replacement of thymine by 5-bromouracil in DNA made bacterial and mammalian cells sensible to the lethal effects of UV light. As shown in Scheme 41 electron transfer occurred only when the reaction was triplet sensitised, and again followed an ET mechanism.

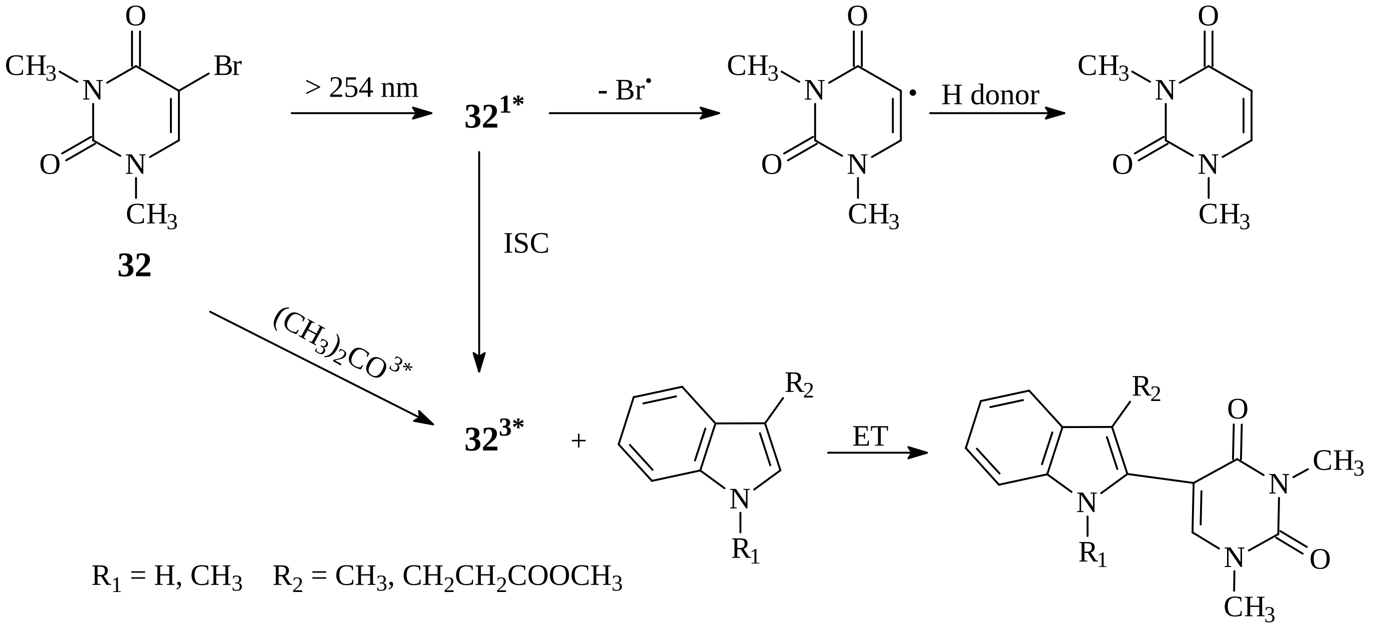
The above reaction was extended to various substituted tryptamines[80] or naphthalenes. In the latter case electron transfer could be favored by the formation of a singlet exciplex.[81]

The benz[*a*]anthracene-7,12-dione skeleton was easily built through the reaction of heteropolycyclic substituted 1,4-naphthoquinone and 1,1-diarylethylenes. The mechanism was similar to that described in Scheme 37, and was followed by a [4+2] cycloaddition.[82]

Scheme 40



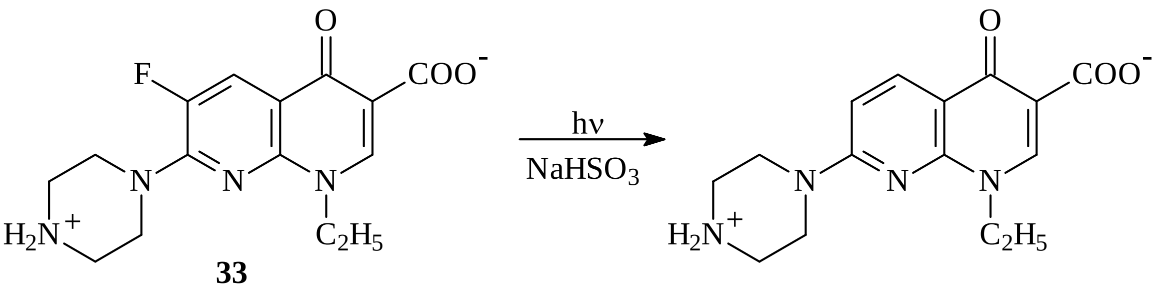
Scheme 41



Dehalogenation is also a smooth way to form Ar-H bonds. In such a way, a particular bromopyridine tethered with an enaminone moiety was debrominated by PET reduction using triethylamine as a donor.[83] The same behavior was observed with 5-bromo-2-methoxypyrimidine when irradiated in CH_3OH. The occurring of the electron transfer path was confirmed by the acceleration of the reaction induced by the presence of good electron donors such as secondary or tertiary amines.[84] Probably the same mechanism is followed in the dehalogenation of 2,4-dimethoxy-6-chloropyrimidine.[85]

An interesting case was observed in the defluorination of some antibacterial drugs belonging to the class of fluoroquinolones. Enoxacin (**33**) (Scheme 42) readily lost a fluoride anion at the radical anion stage after ET to sodium sulfite in aqueous solutions. In turn, the radical was then reduced again by sulfite leading to the fluorine-free quinolone.[86]

Scheme 42

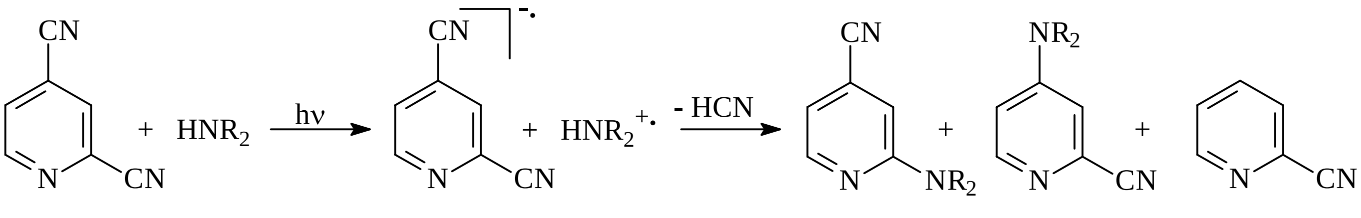


33

5.3 Substitution of a cyano group

Cyanopyridines or pyrazines are excellent electron acceptors in their excited states, and the thus formed radical anions undergo easily radical attack. Ipso-substitution reactions with cyanide loss then ensues. This reaction path was exploited in the synthesis of aminopyridines, important building blocks for the synthesis of pharmaceuticals and bactericides. This target was fulfilled by the photochemical reaction between dicyanopyridines and amines or anilines,[87] despite the fact that the reaction presented a low degree of regioselectivity and was accompanied by the formation of the monocyanopyridine (Scheme 43).

Scheme 43

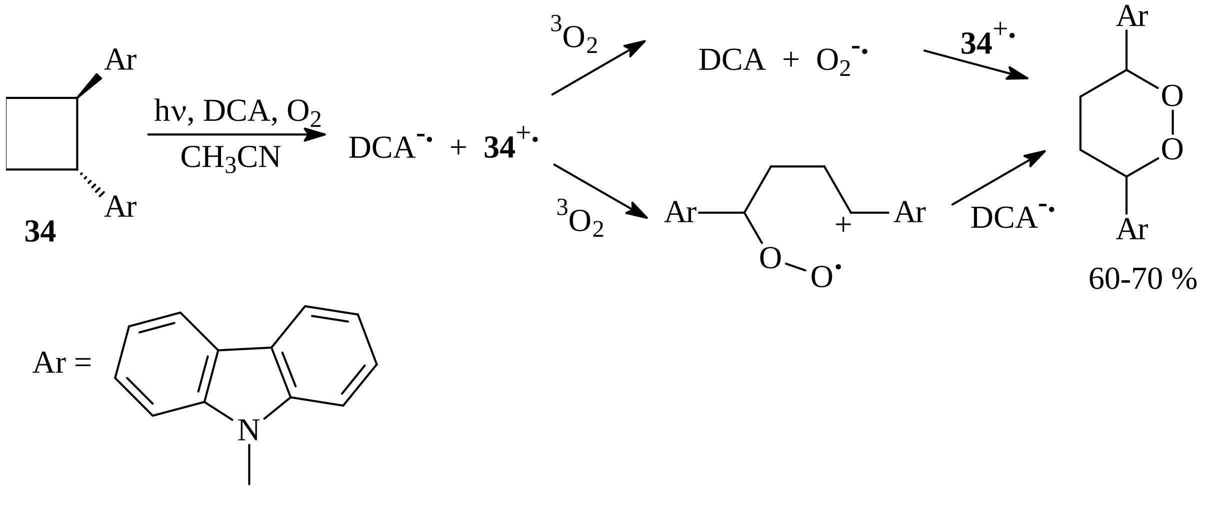


Satisfactory results were obtained in the reaction between dicyanopyridazines and electron donors bearing a trimethylsilyl group, which behaved as an excellent electrofugal group. Ketene silyl acetals or cyclopropanone silyl acetals were suitable precursors respectively of $^{\bullet}CX_2COOCH_3$ and $^{\bullet}CX_2CH_2COOCH_3$ radicals (after phenanthrene mediated oxidation and elimination of the trimethylsilyl cation). Acetic or propanoic esters were the final products.[88] Analogously, *N*-acyl-*N*-trimethylsilylmethylaniline has been used for the generation of aminomethylradicals.[89] Reactions with tertiary amines followed a different pathway when applied on 2-aryl-5,6-dicyanopyrazines. After the electron transfer step, proton transfer occurred and substitution of a cyano group with an hydrogen was the final result.[90]

6. Oxygenation

Only a few examples of PET oxigenation of aromatics are reported in the literature. *trans*-1,2-Di(carbazol-9-yl)cyclobutane (**34**) afforded efficiently 3,6-di(carbazol-9-yl)-1,2-dioxane in the reaction between oxygen and its radical cation formed through oxidation by DCA*. The reaction may follow two different pathways, as illustrated in Scheme 44 where the radical anion has the role of the reducing agent. In the first case reduction occurred by addition of dioxygen to the radical cation whereas in the second one the active specie was superoxide anion $O_2^{-\cdot}$ generated in a secondary electron transfer step.[91]

Scheme 44

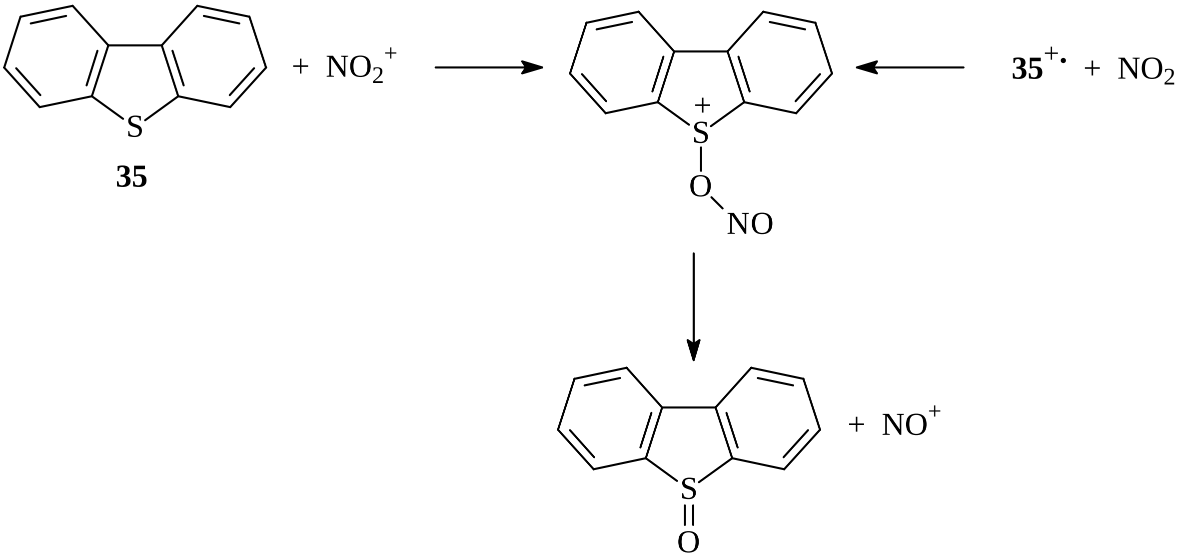


Photooxygenation of furans led to the opening of the ring with the formation of the corresponding enediones. The mechanism of the reaction was not clear but probably involved the formation of peroxy radical cation and perepoxide species.[92]

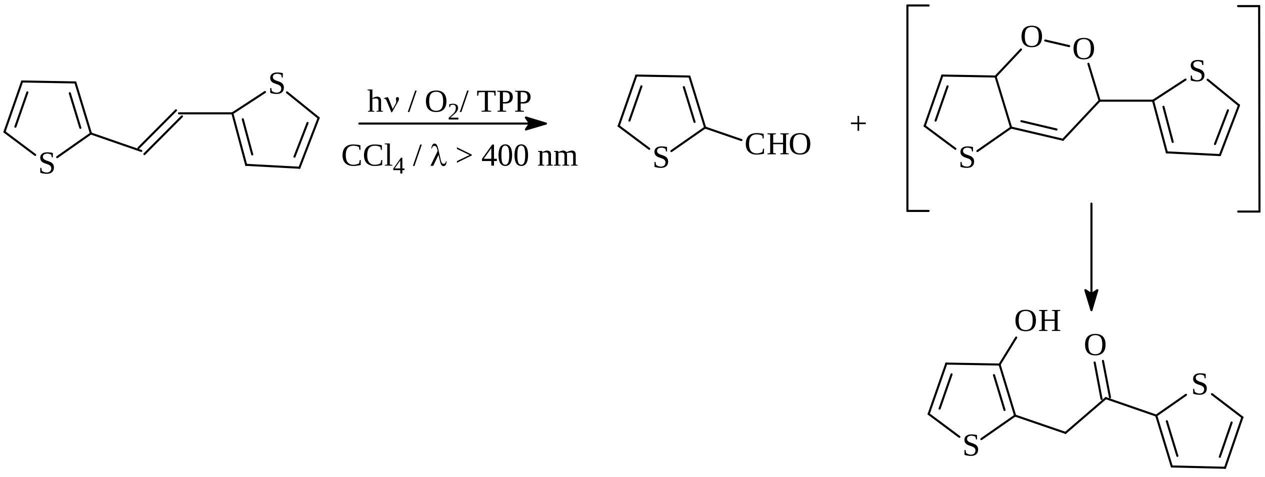
During the photoinduced nitration of dibenzothiophene (**35**) by means of tetranitromethane (*via* the radical cation of the heterocycle), the amount of nitrated derivatives was low when hexafluoropropanol was used as the solvent. Under these conditions a high yield (85%) of dibenzothiophene sulfoxide was obtained.[93] This was due to the reaction of the heterocycle with the oxidant nitrating species formed in solution as illustrated in Scheme 45.

The tetraphenylporphyrin (TPP) photosensitised oxidation of *trans*-1,2-di(2-thienyl)ethylene gave rise to product (**36**) as the major product along with a small amount of 2-thiophenecarboxaldehyde. The reaction occurred via [4 +2] cycloaddition between the starting styrene derivatives and singlet oxygen. On the contrary, *trans*-2-styrylthiophene followed a different path involving superoxide anion, which led to 2-thiophenecarboxaldehyde and benzaldehyde (Scheme 46).[94]

Scheme 45



Scheme 46

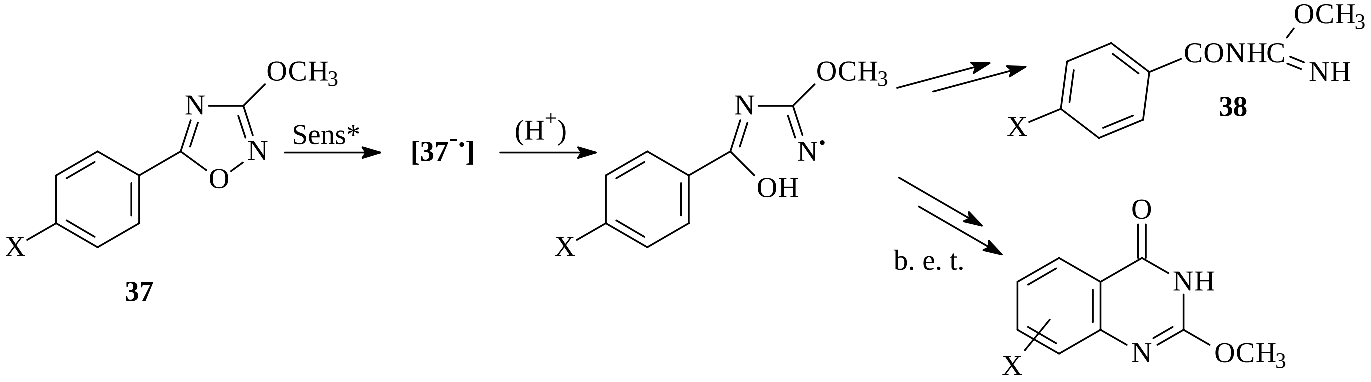


36, Main product

7. Fragmentation

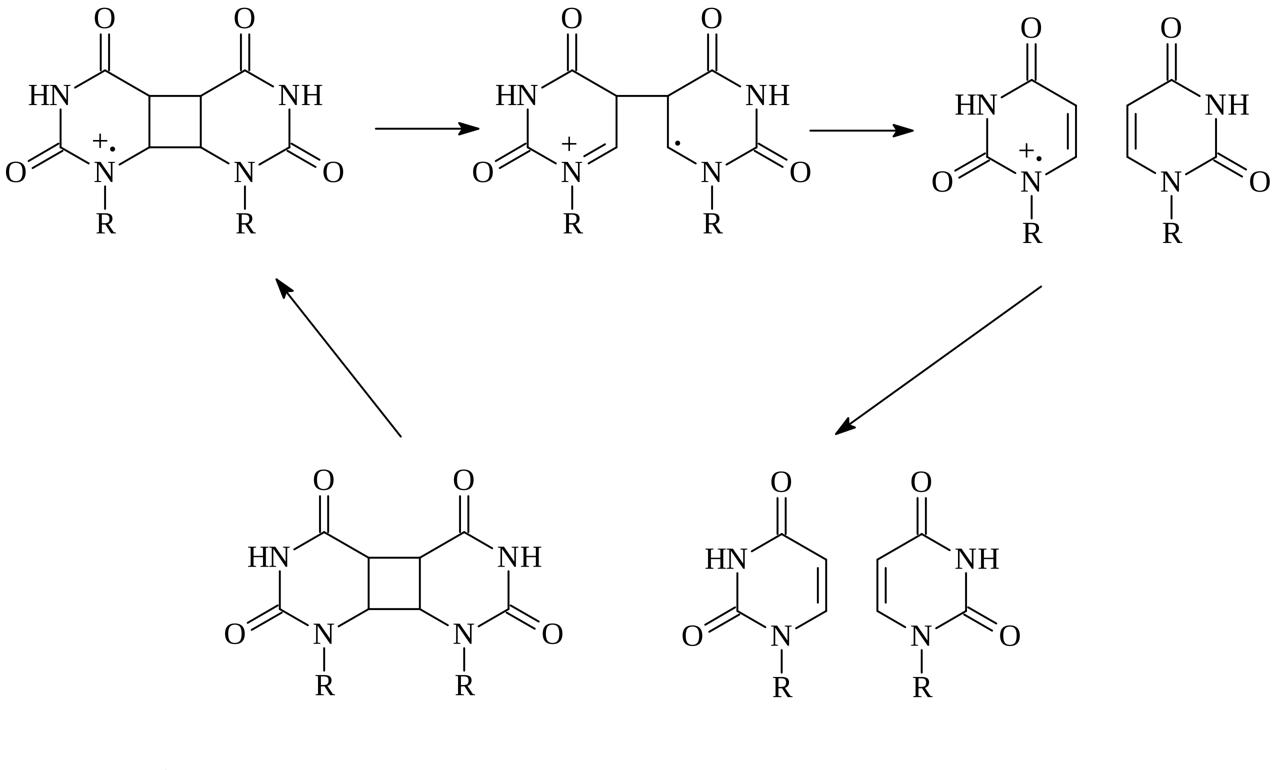
Fragmentation PET reactions are not a very common process for heterocyclic compounds. The weak N-O bond in some 5-aryl-3-methoxy-(or 5-aryl-3-phenyl)-1,2,4-oxadiazoles (**37**) was broken under irradiation in the presence of triphenylene or similar sensitizers, yielding variously substituted quinazolin-4-ones (Scheme 47).[95] The presence of an electron-withdrawing group on the phenyl ring (X = CN, Cl) enhanced significantly the generation of open chain photoreduction products (**38**).

Scheme 47



Electron transfer seems to be involved in the cleavage of pyrimidine photodimers in the UV-damage of DNA induced by DNA photolyase. As shown in Scheme 48 the presence of a quinone intermediate is responsible of the formation of the dimer radical cation and subsequent formation of two molecules of monomers; this path was demonstrated by means of the irradiation of the 6-iodomethyl analogues.[96]

Scheme 48

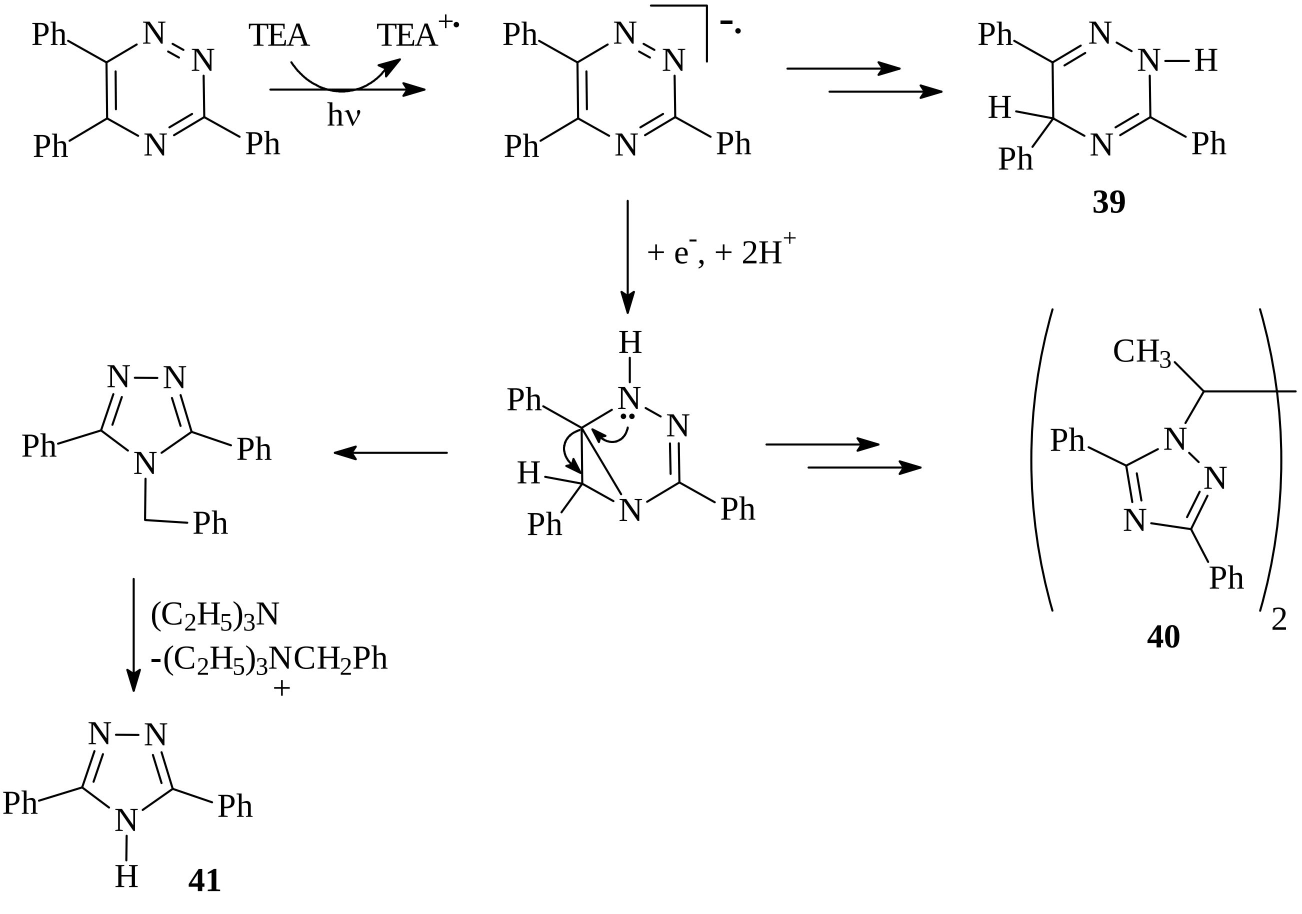


Electron transfer was also invoked in the photoreaction between 1-(1,2,4-triazol-4-yl)-2,4,6-trimethylpyridinium tetrafluoroborate and mesitylene as a trapping agent. As a result, loss of the pyridinium moiety was observed, with the formation of 1-(1,2,4-triazol-1-yl)-2,4,6-trimethylbenzene that was isolated in a higher yield than in the same thermally initiated fragmentation reaction.[97]

8. Rearrangement

Contraction of the ring was observed during the photolysis of 3,5,6-triphenyl-1,2,4-triazine in neat triethylamine (TEA), besides *N*-dealkylation of the amine. The photoreduction product (**39**) was also obtained but the main products were the triazolyl derivatives (**40**) and (**41**) (Scheme 49). These were both debenzylated by the base present in solution.[98]

Scheme 49

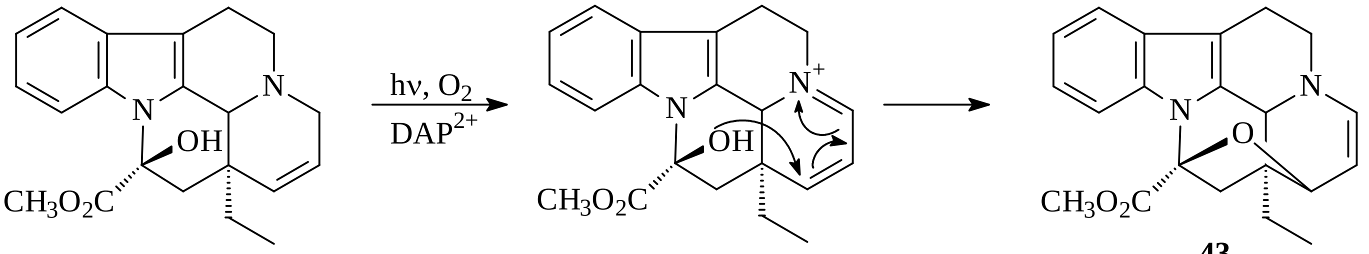


9. Side chain reactions

Finally, we wish to mention some PET reactions belonging to the classes previously described, which involve the side chain rather than the heteroaromatic ring and in some cases represent a smooth entry for the synthesis of useful intermediates.

Photooxidation by means of catalytic amount of the dication of *N*,*N*'-dimethyl-2,7-diazapyrenium (DAP^{2+}) of Δ^{14}-vincine (**42**) generated an iminium ion which was trapped by the hydroxide group functioning as internal nucleophile. This allowed the hemisynthesis of criocerine (**43**) (Scheme 50).[99]

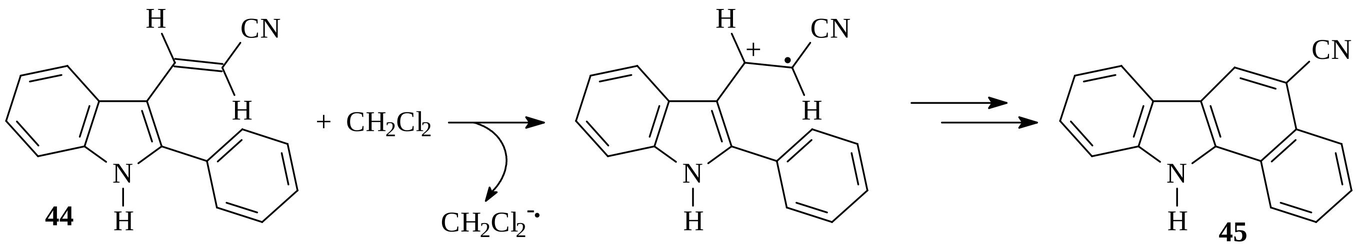
Scheme 50



42 **43**

Fragmentation of the C_{16}-C_{21} bond of the radical cation of catharanthine is an interesting route for a clean access to the cleavamine skeleton.[100] A similar pattern was followed in the monoelectronic oxidation of a dihydropyridinylethylindole in the presence of trimethylsilyl cyanide. The α-cyanoamine thus obtained were employed for the synthesis of indoloquinolizidine alkaloids through a Pictet-Spengler reaction.[101]
A (di)cyanovinyl group when tethered to heteroaromatic rings can change the photochemical behavior of the molecule. Allylation of 1,1-dicyano-2-(2-furyl(thienyl))ethene was obtained through a phenanthrene cosensitized reaction with allyltributylstannane,[102a] whereas cyanovinylindole (**44**) acted as a sensitiser in the cyclization reaction to yield carbazole (**45**) (Scheme 51).[102b]

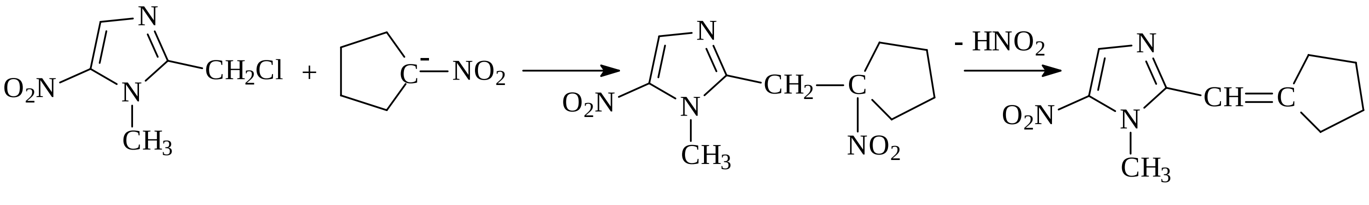
Scheme 51



44 **45**

Finally, $S_{RN}1$ reactions involving the side chain of heteroaromatic compounds have also been reported. Yields depends on the nucleophile used; with the anion from nitroalkanes the alkylation reaction was often followed by nitrous acid elimination. As an example, the reaction on a nitroimidazole derivative is shown in Scheme 52.[103]

Scheme 52



In addition, some $S_{RN}1$ reactions with 2-halomethylfurans or imidazole with nitroalkane anion yielded various benzyl substituted products along with vinylheterocycles.[104]

10. Conclusion

The above presentation shows the diverse scope of photoinduced ET reactions in heterocyclic chemistry. Relatively few examples are present in the literature and most of them involve isolated studies, rather than systematic explorations. Yet some synthetic applications are appealing. As shown in Scheme 3, photoinduced ET is expected to be facile among heterocycles and it can certainly expected that many more useful applications of the strategies described above will be accomplished in the near future.

REFERENCES

1. M. Chanon, M. D. Hawley, and M. A. Fox, in Photoinduced Electron Transfer, ed. by M. A. Fox and M. Chanon, Part A, Elsevier, Amsterdam, 1988, pp. 1-59.
2. A. Alberti, P. Carloni, L. Eberson, L. Greci, and P. Stipa, *J. Chem. Soc., Perkin Trans. 2,* 1997, 887.
3. K. Mizuno, M. Ishii, and Y. Otsuji, *J. Am. Chem. Soc.*, 1981, **103**, 5570.
4. J. M. Bobbitt, C. L. Kulkarni, and J. Willis, *Heterocycles*, 1981, **15**, 495.
5. Measured in 0.51 M aq. NaOH; S. Viraraghavan, *Bull. Chem. Soc. Jpn.*, 1992, **65**, 1101.
6. R. J. Enemaerke, T. B. Christensen, H. Jensen, and K. Daasbjerg, *J. Chem. Soc., Perkin Trans. 2*, 2001, 1620.
7. C. Thobie-Gautier and C. Degrand, *J. Org. Chem.*, 1991, **56**, 5703.
8. M. Genesty, G. Pommatau, and C. Degrand, *Acta Chem. Scand.*, 1999, **53**, 952.
9. J. Ouyang and A. J. Bard, *J. Phys. Chem.*, 1987, **91**, 4058.
10. For a review on the use of pyrylium salts see: M. A. Miranda and H. Garcia, *Chem. Rev.*, 1994, **94**, 1063.
11. For the reduction potentials reported in Scheme 4 see: M. Chanon and L. Eberson, in Photoinduced Electron Transfer, ed. by M. A. Fox and M. Chanon, Part A, Elsevier, Amsterdam, 1988, pp. 409-597.
12. Phthalimides are probably the most worthnoting substrates belonging to this category. Their PET reactions are reviewed elsewhere; see U. C. Yoon and P. S. Mariano, *Acc. Chem. Res.*,2001, **34**, 523.
13. (a) A. Albini and M. Fagnoni, in *Electron Transfer in Chemistry,* Vol. 2, ed. by V. Balzani, Wiley-VCH, 2001, 338. (b) A. Lablache-Combier, in ref. 1 Part. A, pp. 134-312. (c) A. Albini, M. Mella, and M. Freccero, *Tetrahedron*, 1994, **50**, 575.

14. (a) W. Carruthers, in *Cycloaddition Reactions in Organic Synthesis* Pergamon Press 1990. (b) F. Mueller and J. Mattay, *Chem. Rev.*, 1993, **93**, 99.

15. For a detailed description of cation radical cycloadditions reactions see N. L. Bauld, *Tetrahedron,* 1989, **45**, 5307.

16. J. Mattay, *Angew. Chem., Int. Ed. Engl.,* 1987, **26**, 825.

17. T. Wirth and S. Blechert, *Tetrahedron Lett.,* 1992, **33**, 6621.

18. (a) A. Gieseler, E. Steckhan, and O. Wiest, *Synlett,* 1990, 275. (b) A. Gieseler, E. Steckhan, O. Wiest, and F. Knoch, *J. Org. Chem.,* 1991, **56**, 1405.

19. G. C. Calhoun and G. B. Schuster, *J. Am. Chem. Soc.,* 1986, **108**, 8021.

20. O. Wiest, E. Steckhan, and F. Grein, *J. Org. Chem.,* 1992, **57**, 4034.

21. (a) T. Peglow, S. Blechert, and E. Steckhan, *Chem. Comm*., 1999, 433. (b) U. Haberl, E. Steckhan, S. Blechert, and O. Wiest, *Chem. Eur. J.,* 1999, **5**, 2859.

22. (a) O. Wiest and E. Steckhan, *Angew. Chem., Int. Ed. Engl.,* 1993, **32**, 901. (b) O. Wiest and E. Steckhan, *Tetrahedron Lett.,* 1993, **34**, 6391.

23. C. F. Guertler, E. Steckhan, and S. Blechert, *J. Org. Chem.,* 1996, **61**, 4136.

24. J. Botzem, U. Haberl, E. Steckhan, and S. Blechert, *Acta Chem. Scand.,* 1998, **52**, 175.

25. K. Mizuno, R. Kaji, H. Okada, and Y. Otsuji, *J. Chem. Soc., Chem. Comm*., 1978, 594.

26. (a) J. Guilford, II in *Organic Photochemistry,* ed. by A. Padwa, Vol 5, 1981, pp. 1-122. (b) T. Bach, *Synlett,* 2000, 1699.

27. M. D'Auria, R. Racioppi, and G. Romaniello, *Eur. J. Org. Chem.,* 2000, 3265.

28. J. Xue, Y. Zhang, T. Wu, H.-K. Fun, and J.-H. Xu, *J. Chem. Soc., Perkin Trans. 1*, 2001, 183.

29. M. M. Alam and O. Ito, *Bull. Chem. Soc. Jpn.,* 1999, **72**, 339.

30. R. A. Rossi, A. B. Pierini, and A. N. Santiago, *Organic Reactions*, 1999, **54**, 1-271.

31. (a) J. K. Kim and J. F. Bunnett, *J. Am. Chem. Soc.,* 1970, **92**, 7463. (b) R. A. Rossi and J. F. Bunnett, *J. Org. Chem.,* 1973, **38**, 1407.

32. (a) J. V. Hay and J. F. Wolfe, *J. Am. Chem. Soc.,* 1975, **97**, 3702. (b) J. V. Hay, T. Hudlicky, and J. F. Wolfe, *J. Am. Chem. Soc.,* 1975, **97**, 374.

33. (a) A. P. Komin and J. F. Wolfe, *J. Org. Chem.,* 1977, **42**, 2481. (b) D. R. Carver, T. D. Greenwood, J. S. Hubbard, A. P. Komin, Y. P. Sachdeva, and J. F. Wolfe, *J. Org. Chem.,* 1983, **48**, 1180.

34. R. Beugelmans, B. Boudet, and L. Quintero, *Tetrahedron Lett.,* 1980, **21**, 1943.

35. (a) D. R. Carver, A. P. Komin, J. S. Hubbard, and J. F. Wolfe, *J. Org. Chem.,* 1981, **46**, 294. (b) E. A. Oostven and H. C. van der Plas, *Recl. Trav. Chim. Pay-Bas,* 1979, **98**, 441.

36. S. C. Dillender Jr., T. D. Greenwood, S. H. Mukta, and J. F. Wolfe, *J. Org. Chem.*, 1986, **51**, 1184.

37. L. Beltran, C. Galvez, M. Prats, and J. Salgado, *J. Heterocycl. Chem.*, 1992, **29**, 905.

38. M. P. Moon, A. P. Komin, and J. F. Wolfe, *J. Org. Chem.*,1983, **48**, 2392.

39. (a) M. Novi, G. Garbarino, G. Petrillo, and C. Dell'Erba, *J. Org. Chem.*, 1987, **52**, 5382. (b) R. A. Rossi and S. M. Palacios, *J. Org. Chem.*, 1981, **46**, 5300.

40. R. Beugelmans, M. Bois-Choussy, and B. Boudet, *Tetrahedron*, 1983, **39**, 4153.

41. R. R. Goehring, Y. P. Sachdeva, J. S. Pisipati, M. C. Sleevi, and J. F. Wolfe, *J. Am. Chem. Soc.*, 1985, **107**, 435.

42. (a) S. Kyushin, Y. Nakadaira, and M. Ohashi, *Chem. Lett.*, 1990, 2191. (b) E. Baciocchi, G. Doddi, M. Ioele, and G. Ercolani, *Tetrahedron*, 1993, **49**, 3793.

43. For a detailed description of the photoinduced electron transfer functionalization of the 10-methylacridinium ion see: N. Satoh and S. Fukuzumi in *Reviews on Heteroatom Chemistry*, Vol 20, pp. 249-281.

44. (a) S. Fukuzumi, S. Kuroda, and T. Tanaka, *J. Chem. Soc., Chem. Comm.*, 1986, 1553. (b) S. Fukuzumi, T. Kitano, and T. Tanaka, *Chem. Lett.*, 1989, 1231.

45. (a) S. Fukuzumi, M. Fujita, and J. Otera, *J. Chem. Soc., Chem. Comm.*, 1993, 1536. (b) M. Fujita, A. Ishida, S. Takamuku, and S. Fukuzumi, *J. Am. Chem. Soc.*,1996, **118**, 8566.

46. (a) S. Fukuzumi, T. Kitano, and K. Mochida, *Chem. Lett.*, 1989, 2177. (b) S. Fukuzumi, T. Kitano, and K. Mochida, *J. Chem. Soc., Chem. Comm.*, 1990, 1236. (c) S. Fukuzumi, K. Ohkubo, T. Suenobu, K. Kato, M. Fujitsuka, and O. Ito, *J. Am. Chem. Soc.*, 2001, **123**, 8459.

47. F. Minisci, F. Fontana, T. Caronna, and L. Zhao, *Tetrahedron Lett.*, 1992, **33**, 3201.

48. M. Fujita and S. Fukuzumi, *J. Chem. Soc., Perkin Trans. 2,* 1993, 1915.

49. U. C. Yoon, S. L. Quillen, and P. S. Mariano, *Tetrahedron Lett.*, 1982, **23**, 919.

50. R. Suau, F. Najera, and R. Rico, *Tetrahedron*, 1999, **55**, 4019.

51. M. Schmittel, G. Viola, F. Dall'Acqua, and G. Morbach, *Chem. Comm.*, 2003, 646.

52. D. Zhu and J. K. Kochi, *Organometallics*, 1999, **18**, 161.

53. (a) C. Pac, A. Nakasone, and H. Sakurai, *J. Am. Chem. Soc.*, 1977, **99**, 5806. (b) T. Majima, C. Pac, A. Nakasone, and H. Sakurai, *J. Am. Chem. Soc.*, 1981, **103**, 4499.

54. (a) P. Grandclaudon, A. Lablanche-Combier, and C. Parkanyi, *Tetrahedron*, 1973, **29**, 651. (b) P. Grandclaudon, and A. Lablanche-Combier, *J. Chem. Soc., Chem. Comm.*, 1971, 892.

55. A. Buquet, A. Couture, A. Lablanche-Combier, and A. Pollet, *Tetrahedron*, 1981, **37**, 75.

56. C. P. Butts, L. Eberson, R. Gonzalez-Luque, C. M. Hartshorn, M. P. Hartshorn, M. Merchan, W. T. Robinson, B. O. Roos, C. Vallance, and B. R. Wood, *Acta Chem. Scand.*, 1997, **51**, 984.

57. (a) T. Kubota and H. Sakurai, *Chem. Lett.,* 1972, 923. (b) T. Kubota and H. Sakurai, *Chem. Lett.,* 1972, 1249.

58. J. J. McCullough, W. S. Wu, and C. W. Huang, *J. Chem. Soc., Perkin Trans. 2,* 1972, 370.

59. K. Yamasaki, T Matsuura, and I. Saito, *J. Chem. Soc., Chem. Comm.*, 1974, 944.

60. (a) S. Naruto and O. Yonemitsu, *Tetrahedron Lett.,* 1971, 2297. (b) S. Naruto and O. Yonemitsu, *Chem. Pharm. Bull.*, 1972, **20**, 2163.

61. R. J. Sundberg, in *Organic Photochemistry*, Vol. 6, ed. by. A. Padwa, Marcel Dekker Inc. New York and Basel 1983, pp. 121.

62. R. J. Sundberg and J. D. Bloom, *J. Org. Chem.,* 1980, **45**, 3382.

63. (a) S. Naruto and O. Yonemitsu, *Tetrahedron Lett.*, 1975, 3399. (b) S. Naruto and O. Yonemitsu, *Chem. Pharm. Bull.*, 1980, **28**, 900. (c) A. Wu and V. Snieckus, *Tetrahedron Lett.*, 1975, 2057. (d) R. J. Sundberg and F. X. Smith, *J. Org. Chem.,* 1975, **40**, 2613. (e) R. J. Sundberg, J. G. Luis, R. L. Parton, S. Schreiber, P.C. Srinivasan, P. Lamb, P. Forcier, and R. F. Bryan, *J. Org. Chem.,* 1978, **43**, 4859. (f) T. Kobayashi, T. F. Spande, H. Aoyagi, and B. Witkop, *J. Med. Chem.*, 1969, **12**, 636.

64. N. G. Anderson and R. G. Lawton, *Tetrahedron Lett.*, 1977, 1843.

65. S. M. Bonesi and R. Erra-Balsells, *An. Asoc. Quim. Argentina*, 1999, **87**, 127.

66. A. Gaplovsky, S. Toma, J.-L. Luche, B. Jakubikova, K. Gaplovska, and R. Mracnova, *J. Chem. Soc., Perkin Trans. 2,* 2002, 652.

67. Q.-Y. Chen and Z.-T. Li, *J. Chem. Soc., Perkin Trans. 1,* 1993, 645.

68. (a) K. Maruyama, T. Otsuki, and H. Tamiaki *Bull. Chem. Soc. Jpn.* 1985, **58**, 3049. (b) K. Maruyama and H. Tamiaki *Bull. Chem. Soc. Jpn.*, 1987, **60**, 3049. (c) K. Maruyama and T. Otsuki, *Chem. Lett.,* 1977, 851. (d) K. Maruyama and T. Otsuki, *Bull. Chem. Soc. Jpn.,* 1977, **50**, 3429.

69. (a) Q.-Y. Chen and Z.-T. Li, *J. Chem. Soc., Perkin Trans. 1,* 1993, 1705. (b) Q.-Y. Chen and Z.-T. Li, *J. Org. Chem.,* 1993, **58**, 2599.

70. C. P Butts, L. Eberson, M. P. Hartshorn, F. Radner, and B. R. Wood, *Acta Chem. Scand.*, 1997, **51**, 476.

71. J. Xu, J. He, and Y. Qian, *J. Chem. Soc., Chem. Comm.*, 1991, 714.

72. M. D’Auria, *Tetrahedron,* 1991, **47**, 9225.

73. (a) G. A. Russell, D. Guo, W. Baik, and S. J. Herron, *Heterocycles,* 1989, **28**, 143. (b) G. A. Russell, R. Rajaratnam, L. Wang, B. Z. Shi, B. H. Kim, and C. F. Yao, *J. Am. Chem. Soc.*, 1993, **115**, 10596.

74. K. Yoshida, *J. Chem. Soc., Chem. Comm.*, 1978, 1108.

75. (a) M. D’Auria, A. De Mico, F. D’Onofrio, and G. Piancatelli, *J. Chem. Soc., Perkin Trans. 1,*

1987, 1777. (b) M. D'Auria, R. Antonioletti, A. De Mico, and G. Piancatelli, *Heterocycles*, 1986, **24**, 1575. (c) R. Antonioletti, M. D'Auria, A. De Mico, G. Piancatelli, and A. Scettri, *J. Chem. Soc., Perkin Trans. 1,* 1985, 1285. (d) R. Antonioletti, M. D'Auria, F. D'Onofrio, G. Piancatelli, and A. Scettri, *J. Chem. Soc., Perkin Trans. 1,* 1986, 1755. (e) R. Antonioletti, M. D'Auria, A. De Mico, G. Piancatelli, and A. Scettri, *Tetrahedron*, 1985, **41**, 3441.

76. M. D'Auria, A. De Mico, F. D'Onofrio, and G. Piancatelli, *J. Org. Chem.,* 1987, **52**, 5243.

77. B. Taljaard and G. J. Burger, *Adv. Synth. Catal.*, 2002, **344**, 1111.

78. M. D'Auria, G. Piancatelli, and T. Ferri, *J. Org. Chem.*, 1990, **55**, 4019.

79. (a) S. Ito, I. Saito, and T. Matsuura, *J. Am. Chem. Soc.*, 1980, **102**, 7535. (b) T. Matsuura, I. Saito, S. Ito, H. Sugiyama, and T. Shinmura, *Pure Appl. Chem.*, 1980, **52**, 2705. (c) I. Saito, S. Ito, and T. Matsuura, *J. Am. Chem. Soc.*, 1978, **100**, 2901.

80. S. Ito, I. Saito, and T. Matsuura, *Tetrahedron Lett.*, 1979, 4067.

81. S. Ito, I. Saito, and T. Matsuura, *Tetrahedron* 1981, **37**, 45.

82. K. Maruyama, T. Otsuki, and S. Tai, *J. Org. Chem.*, 1985, **50**, 52.

83. Y. Blache, M.-E. Sinibaldi-Troin, M. Hichour, V. Benezech, O. Chavignon, J.-C. Gramain, J.-C. Teulade, and J.-P. Chapat, *Tetrahedron,* 1999, **55**, 1959.

84. (a) J. Nasielski, A. Kirsch-Demesmacker, P. Kirsch, and R. Nasielski-Hinken, *Chem. Comm.,* 1970, 302. (b) J. Nasielski, A. Kirsch-Demesmacker, and R. Nasielski-Hinken, *Tetrahedron,* 1972, **28**, 3767. (c) J. Nasielski, and A. Kirsch-Demesmacker, *Tetrahedron*, 1973, **29**, 3153.

85. L. R. Hamilton and P. J. Kropp, *Tetrahedron Lett.*, 1971, 1625.

86. (a) A. Profumo, E. Fasani, and A. Albini, *Heterocycles,* 1999, **51**, 1499. (b) E. Fasani, F. F. Barberis Negra, M. Mella, S. Monti, and A. Albini, *J. Org. Chem.,* 1999, **64**, 5388.

87. (a) R. Bernardi, T. Caronna, S. Morocchi, M. Ursini, and B. M. Vittimberga, *J. Chem. Soc., Perkin Trans. 1,* 1990, 97. (b) R. Bernardi, T. Caronna, S. Morocchi, and B. M. Vittimberga *J. Chem. Soc., Perkin Trans. 2,* 1991, 1411. (c) R. Bernardi, T. Caronna, G. Poggi, and B. M. Vittimberga, *J. Heterocycl. Chem.,* 1994, **31**, 903. (d) T. Caronna, B. M. Vittimberga, M. E. Kornn, and W. G. McGimpsey, *J. Photochem. Photobiol., A,* 1995, **90**,137.

88. K. Mizuno, G. Konishi, T. Nishiyama, and H. Inoue, *Chem. Lett.,* 1995, 1077.

89. M. Igarashi and M. Tada, *Heterocycles*, 1994, **38**, 2277.

90. (a) M. Tada, H. Hamazaki, and H. Hirano, *Bull. Chem. Soc. Jpn.*, 1982, **55**, 3865. (b) M. Tada and K. Tsuzuki, *Chem. Lett.*, 1984, 415.

91. K. Mizuno, K. Marukami, N. Kamiyama, and Y. Otsuji, *J. Chem. Soc., Chem. Comm.*, 1983, 462.

92. N. Manoj and K. R. Gopidas, *J. Photochem. Photobiol., A*, 1995, **85**, 53.

93. C. P. Butts, L. Eberson, M. P. Hartshorn, F. Radner, W. T. Robinson, and B. R. Wood, *Acta Chem. Scand.*, 1997, **51**, 839.

94. K. Song, M.-L. Peng, M. Xu, L.-Z. Wu, L.-P- Zhang, and C.-H. Tung, *Tetrahedron Lett.*, 2002, **43**, 6633.

95. S. Buscemi, A. Pace, N. Vivona, T. Caronna, and A. Galia, *J. Org. Chem.*, 1999, **64**, 7028.

96. D. Burdi and T. P. Begley, *J. Am. Chem. Soc.*, 1991, **113**, 7768.

97. R. A. Abramovitch, J. M. Beckert, H. H. Gibson Jr., A. Belcher, G. Hundt, T. Sierra, S. Olivella, W. T. Pennigton, and A. Solè, *J. Org. Chem.*, 2001, **66**, 1242.

98. D. Doepp, W. A. F. Youssef, A. Dittmann, A. M. Kaddah, A. A. Shalaby, and Y. M. Naguib, *J. Inf. Recording*, 2000, **25**, 57.

99. J. Santamaria, *Pure Appl. Chem.*, 1995, **67**, 141.

100. G. Cocquet, P. Rool, and C. Ferroud, *Tetrahedron Lett.*,2001, **42**, 839.

101. J. Santamaria, M. T. Kaddachi, and C. Ferroud, *Tetrahedron Lett.*,1992, **33**, 781.

102. (a) K. Mizuno, S. Toda, and Y. Otsuji, *Chem. Lett.*, 1987, 203. (b) J. Claret, I. Fernandez, C. Galvez, and R. Lapouyade, *J. Photochem. Photobiol., A*, 1991, **55**, 347.

103. M. P. Crozet, J. M. Surzur, P. Vanelle, C. Ghiglione,and J. Maldonado, *Tetrahedron Lett.*, 1985, **26**, 1023.

104. (a) C. D. Beadle and W. R. Bowman, *J. Chem. Res. (S)*, 1985, 150. (b) M. P. Crozet, J. M. Surzur, P. Vanelle, C. Ghiglione, and J. Maldonado, *Tetrahedron Lett.*,1985, **26**, 1023.