once esoteric, the TG technique is now coming into its own, and it will find a wide variety of chemical applications in the coming years.

Mechanistic and Synthetic Aspects of Amine–Enone Single Electron Transfer Photochemistry

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The recognition that single electron transfer (SET) can be a dominant reaction pathway followed when electronic excited state species interact with ground-state donors or acceptors has had a profound impact on the field of organic photochemistry. This has been especially important in the design, mechanistic analysis, and synthetic applications of new photochemical reactions. Both theoretical[1] and empirical relationships[2] now available enable an accurate estimation of the rate constants (k_{SET}) for excited-state SET based on experimentally measured redox potentials and excited-state energies. Consequently, relative efficiencies of SET versus other excited state decay pathways can be evaluated. In addition, SET between neutral excited donor–acceptor pairs leads to generation of ion radicals, intermediates which can undergo rapid, novel, and frequently predictable reactions to produce secondary radical or charged intermediates in routes for product formation.[3] In contrast to classical photochemical reactions where the pathways followed are governed by the characteristic bonding properties in excited states, the nature of excited-state SET reactions is controlled primarily by the chemistry of the ion radical interme-

Scheme I

(E=H or SiMe₃)

Scheme II
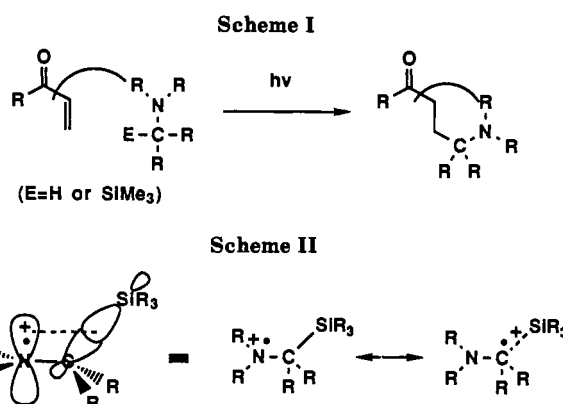
diates. As a result, it is not surprising that the majority of new organic photochemical processes discovered in recent years operate via SET mechanisms and that a large number of these have found their way into the organic synthetic repertoire.[4]

This Account focuses on a class of SET photochemical processes that we have explored extensively. The specific reactions involve photoadditions and photocyclizations of α,β-unsaturated ketone–tertiary amine systems (Scheme I). In reviewing the key observations, we will attempt to demonstrate how an understanding of the factors governing SET reaction efficiencies and ion radical chemistry can be used to mechanistically analyze new excited-state SET processes and to develop their synthetic potential. To establish the background

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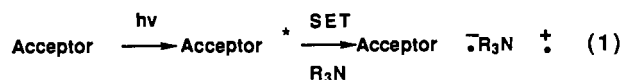(3) Davidson, R. S. *Molecular Association*; Foster, R., Ed.; Academic Press: London, 1975; Vol. 1. Lablache-Combier, A. *Bull. Soc. Chim. Fr.* 1972, *12*, 4791. Davidson, R. S. *Adv. Phys. Org. Chem.* 1983, *19*, 1. Julliard, M.; Chanon, M. *Chem. Rev.* 1983, *83*, 425.
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Scheme III
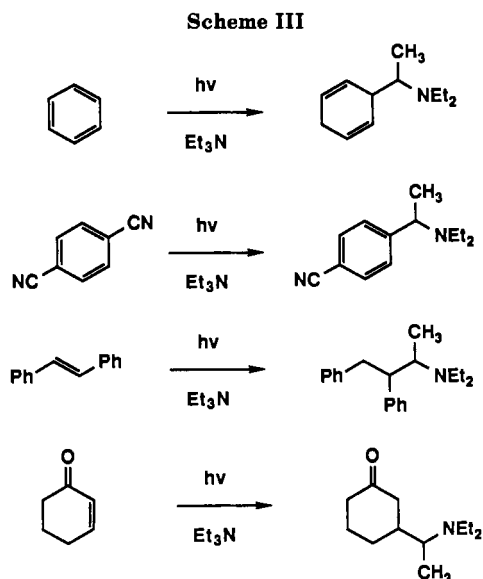
for our investigations, we will first present a brief survey of the salient features of tertiary amine SET chemistry before discussing the initial exploratory work which brought to our attention the intriguing mechanistic characteristics and the synthetic potential of SET-promoted amine–enone photochemical reactions.

SET Chemistry of Tertiary Amines. Tertiary amines can serve as electron donors in SET photoreactions (eq 1).[5] The thermodynamic facility of these processes is determined by the difference between the amine oxidation potentials ($E_{1/2}(+)$) and the acceptor excited state reduction potentials ($E_{1/2}*(-)$). Tertiary amines are among the most easily oxidized of neutral organic substances as reflected in their low $E_{1/2}(+)$ values (+0.8 to +0.5 V). The observed effects of substitution on $E_{1/2}(+)$ (e.g., larger for amides than carbamates, $E_{1/2}(+) = +1.6$ to +1.8 V) are easy to forecast. Pertinent to the discussion below are the effects of α-substitution by group IV metal containing ligands (e.g., R_3Si and R_3Sn) on $E_{1/2}(+)$ of amines. Yoshida[6] and Owens[7] have demonstrated that α-trialkylsilyl amines and carbamates are more easily oxidized than their non-silicon analogues. These trends, detected also for allyl- and benzylsilanes[8] and for α-silyl ethers and thioethers,[9] result from hyperconjugative stabilization of the amine cation radicals through σ_{C-MR_3} and p_N orbital overlap (Scheme II).[6a,10]

$$\text{Acceptor} \xrightarrow{h\nu} \text{Acceptor}^* \xrightarrow[R_3N]{SET} \text{Acceptor} \cdot^- R_3N \cdot^+ \quad (1)$$

Tertiary amines serve as efficient one-electron donors (k_{SET} = ca. k_{diff} = 1 × 10^{10} M^{-1} s^{-1}) to a wide variety of excited organic substrates ranging from arene and

cyanoarene singlets ($E_{1/2}*^1(-) = +1$ to +3 V) to saturated ketone, phenone, and unsaturated ketone triplets ($E_{1/2}*^3(-) = +0.2$ to +0.9 V).

SET oxidation of amines leads to formation of amine cation radicals (aminium radicals), reactive intermediates with a rich history in organic chemistry (e.g., Wurster salts, Hofmann–Loeffler–Freytag reaction intermediates). An old but still important review of the structural, spectroscopic, and chemical properties of these ion radicals has been provided by Nelsen and his co-workers.[11] Perhaps the most common reaction of tertiary aminium radicals is α-CH deprotonation to produce α-amino radicals (eq 2). Pertinent examples of the chemical consequences of sequential SET–deprotonation routes are found in tertiary amine photoadditions to arenes,[12] cyanoarenes,[13] alkenes,[14] and unsaturated ketones[15,16] (Scheme III).

$$(2)$$
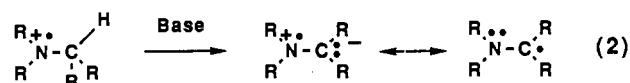
A number of the features of tertiary amine cation radical α-CH deprotonation have received detailed study. For example, pulse radiolysis investigations by Das and von Sonntag[17] have shown that the pK_a (H$_2$O, 25 °C) of Me$_3$N$^{•+}$ is ca. 8. A pK_a value of 10 (MeCN, 25 °C) for the more stable N-methyl-N,N-bis(p-methoxyphenyl)aminium radical has come from estimates made Dinnocenzo and Banach.[18] These studies also demonstrate that the rates of tertiary amine cation radical α-CH deprotonation are large. Accordingly, proton transfer from Me$_3$N$^{•+}$ to Me$_3$N in H$_2$O was found[17] to have a bimolecular rate constant of ca. 7 × 10^8 M^{-1} s^{-1}. The stopped-flow kinetic study of Dinnocenzo and Banach[18] has shown that the (p-MeOC$_6$H$_4$)$_2$NMe cation radical is deprotonated by a number of isoquinuclidine bases with rate constants (MeCN) of ca. 1 × 10^5 M^{-1} s^{-1}.

The picosecond laser flash photolysis investigations by Peters and his collaborators[19] offer a picture of the dynamics of processes following photoinduced SET in tertiary amine–ketone systems. SET from amines to triplet benzophenone (BP) was observed to occur at diffusion-controlled rates in MeCN to produce the amine cation and BP anion radicals in a solvent-separated ion radical pair (SSIRP).[19a] The SSIRP then

(5) For a comprehensive review of amine SET photochemistry, see: Pienta, N. J. *Photoinduced Electron Transfer*; Fox, M. A., Chanon, M., Eds.; Elsevier: New York, 1988; Part C.
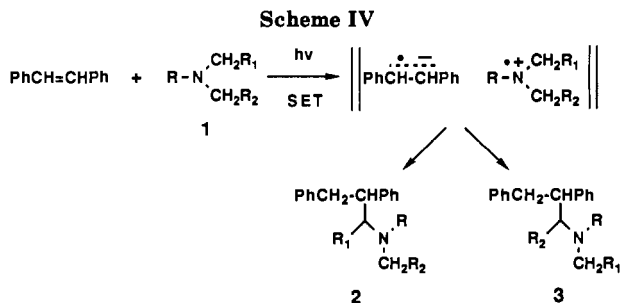
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Scheme IV

Table I
Substituent Control of Tertiary Amine Cation Radical Kinetic Acidities Determined through Use of the Stilbene–Amine Photochemical System
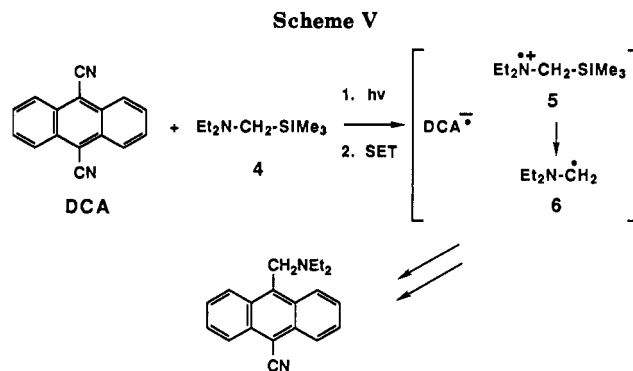
$$Y_2\overset{+\cdot}{N}CH_2\text{-R} \longrightarrow Y_2\overset{\cdot}{N}\overset{\cdot}{C}H\text{-R}$$

R	rel kinetic acidity	R	rel kinetic acidity
CH_3	1	H	2.2
$CH=CH_2$	1	CO_2CH_3	4.6
Ph	2.0	$C\equiv CH$	>200

collapses within ca. 300 ps to a contact ion radical pair (CIRP), where proton transfer takes place with a rate constant of ca. 2×10^9 s^{-1} to produce the BP ketyl and α-amino radicals. In addition, Simon and Peters[19a] found that k_{SET} in the DABCO–BP triplet pair was nearly equal to k_{diff} in solvents of greatly different polarities (e.g., 1.3×10^{10} M^{-1} s^{-1} in C_6H_6 and 1.7×10^{10} M^{-1} s^{-1} in MeCN). In contrast, the rates of proton transfer in the BP$^{\cdot-}$Ph$_2$NMe$^{\cdot+}$ CIRP are affected by solvent, increasing as solvent polarity decreases (e.g., 5×10^6 s^{-1} in C_6H_6 and 1.6×10^6 s^{-1} in pyridine).[19b] Both the rates and regioselectivities for proton transfer in aryl ketone–tertiary amine CIRPs were observed to be dependent upon the relative orientation of the charged radical partners.[20] Finally, Simon and Peters[19c,d] described the effects of polar protic solvents and alkali metal perchlorate salts on the dynamics for interconversion between SSIRP and CIRP intermediates. Their results suggest that SSIRP formation is preferred under conditions where stabilization of the BP$^{\cdot-}$ by H-bonding or metal cation complexation is possible.

Another interesting issue regarding tertiary amine cation radicals concerns the influence of substituents on the kinetic acidity of α-CH protons. An extensive investigation of this question has been conducted by Lewis and his co-workers.[21] Product distributions (2:3 in Scheme IV) resulting from photoreactions of unsymmetric amines 1 with stilbene were transformed into relative α-CH kinetic acidities of the intermediate aminium radical. The data obtained (Table I) demonstrate that in these processes, where proton transfer occurs in a CIRP intermediate,[21] rates of amine cation radical deprotonation are governed mainly by synergistic steric and stereoelectronic effects. Lewis[21] concluded that energies of transition states for proton transfer in the CIRP are influenced by steric strain associated with internal interactions in the amine cation radical com-

Scheme V

ponent. The energetic consequences of intercomponent interactions between the stilbene anion and aminium radicals and of the orientation of partners in the CIRP of course may also be important.

Chemistry of α-Silyl Amine Cation Radicals. Amine cation radicals having electrofugal groups other than protons at α-positions also undergo heterolytic fragmentations. Decarboxylations of aminium radicals derived from α-amino acids[22] and retro-aldol cleavage of α-amino alcohol cation radicals[23] are examples of this. In recent years, another general cation radical fragmentation process involving nucleophile-assisted displacement of group IV metal substituents (R$_3$M where M = Si, Sn, or Ge, eq 3) has been uncovered,[24] thoroughly explored,[25] and used in the design of synthetically relevant SET-photochemical transformations.[26] An example of the role played by this process (5 → 6 in Scheme V) is found in the photoaddition of tertiary α-silyl amine 4 to 9,10-dicyanoanthracene (DCA).[27]

Initial predictions about the facility of cation radical demetalation reactions generalized in eq 3 came from considerations of the thermodynamic stabilization enjoyed by these charged radical intermediates owing to $\sigma_{C-metal}$-$p_{cation\,radical}$ overlap. It was reasoned that the
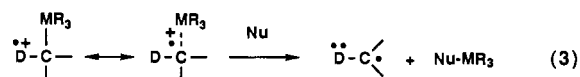
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C–M bond would be weakened by this interaction (one electron bond character) and that positive charge density would reside heavily at the electropositive metal center. Thus, as with related β-R$_3$M substituted cation analogues,[28] nucleophilic attack at the metal in concert with C–M rupture should be fast and dominant over other pathways like α-deprotonation[29] or nucleophile addition to the D$^{\bullet+}$ centers. Early observations[24a] that SET-promoted photoreactions of the pyrrolinium salts with allylsilanes led to exclusive formation of allylpyrrolidines provided initial support for this proposal. More recent studies[25a,b,d,e,h] probing the rates of allyl- and benzylsilane cation radical desilylations have demonstrated that these fragmentation processes are exceptionally fast even when the participating nucleophiles are of low silophilicity (e.g., MeCN). For example, the rates of desilylation of [PhCH$_2$SiMe$_3$]$^{\bullet+}$ and related cation radicals in MeCN at 25 °C fall in the range of ca. 5 × 10^8 s^{-1}.

These observations suggested that sequential SET-desilylation pathways operating on α-silyl amines could serve as regioselective methods for α-amino radical generation. Stimulated by both this thought and our interests in developing synthetically useful SET-photochemical reactions, we outlined a program to investigate photoaddition reactions of α-silyl amines with excited-state acceptors. Our initial work focused on the reactions of α-silyl amine 4 with α,β-unsaturated cyclic ketones. Earlier studies by Cookson,[15a] Pienta,[15b] and Schuster,[15c] which demonstrated that triethylamine reacts with cyclohexenone triplets via SET routes to produce the β-adducts (Scheme III), served as our guide.

At the outset we anticipated that photoadditions of silyl amine 4 to cyclohexenones would follow SET pathways and that adducts would be generated via routes involving selective desilylation of the intermediate aminium radicals followed by radical coupling. In addition, since α-amino radicals are electron-rich species (high-energy SOMOs), they should add efficiently to electron-deficient olefins. Consequently, we reasoned that SET-photosensitized methods might be applied in promoting β-adduct formation by a sequence involving α-amino radical generation and addition to cyclohexenones. Studies of these processes have led to a greater understanding of the factors that control the scope, limitations, and synthetic potential of silyl amine–cyclohexenone photoaddition and photocyclization reactions.

α-Silyl Amine–Enone SET Photochemistry

Initial Observations and Mechanistic Analysis. Our inaugural efforts[30] began with an exploration of photoaddition reactions of the tertiary α-silyl amine 4 to conjugated cyclohexenones and gave rise to a number of puzzling at first but, later, interesting observations. We noted that two types of adducts are produced in these photoadditions, as exemplified by the reaction of silyl amine 4 with the cyclohexenones 7, which generates TMS-containing adducts 8 and non-TMS adducts 9

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Scheme VI
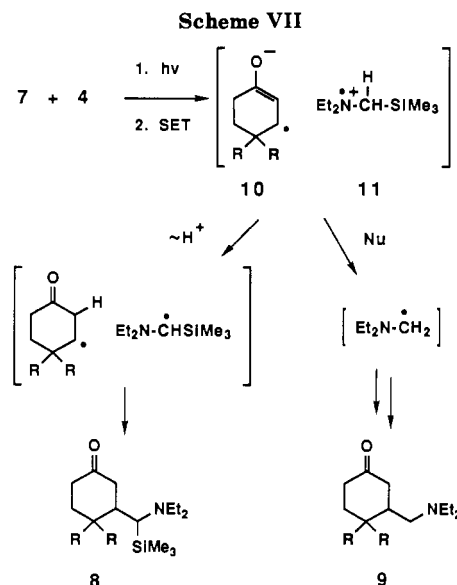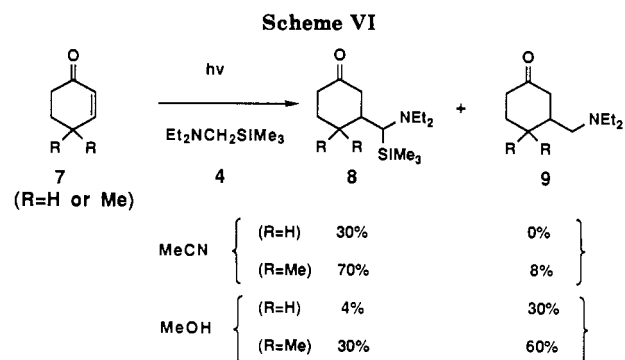
Scheme VII

(Scheme VI). Especially intriguing was the fact that the TMS and non-TMS adduct distributions varied greatly with what appeared to be subtle changes in the photoreaction solvent. TMS adducts predominate in the slightly less polar, aprotic solvent MeCN while in the more polar, protic solvent MeOH the non-TMS adducts are preferentially formed. Equally curious was the comparison of these results with those from studies of the photoaddition of silyl amine 4 to the acceptor DCA in MeCN, where only a non-TMS adduct (Scheme V) is formed. Thus, it was clear that these reactions are mechanistically more complicated than at first imagined and that the solvent and acceptor effects are linked to the properties of the silyl aminium radical intermediate.

The source of these and other effects on the chemoselectivity (i.e., TMS vs non-TMS adduct formation) of SET photoadditions of α-silyl amines was revealed in a thorough study[31] probing the influence of solvents, added salts, and added bases on the ratio of adducts (9:8) arising from reaction of 4 with cyclohexenone 7 (R = Me). The key observations made were that the 9:8 ratio increases dramatically with (1) changes from nonpolar, aprotic solvents (e.g., 0.05 in cyclohexane) to polar and, more importantly, protic solvents (e.g., 2.97 in MeOH and 4.08 in 25% H$_2$O–MeOH) and (2) addition of LiClO$_4$ (e.g., from 0.16 in MeCN to 2.68 in 0.13 M LiClO$_4$ in MeCN). These results implicate a mechanism (Scheme VII) for the photoadditions in which the

(31) Hasegawa, E.; Xu, W.; Mariano, P. S.; Yoon, U. C.; Kim, J. U. *J. Am. Chem. Soc.* 1988, *110*, 8099.

Scheme VIII

12

13

Scheme IX

14

15

Scheme X

16　　　　　　17

18　　　　　　19
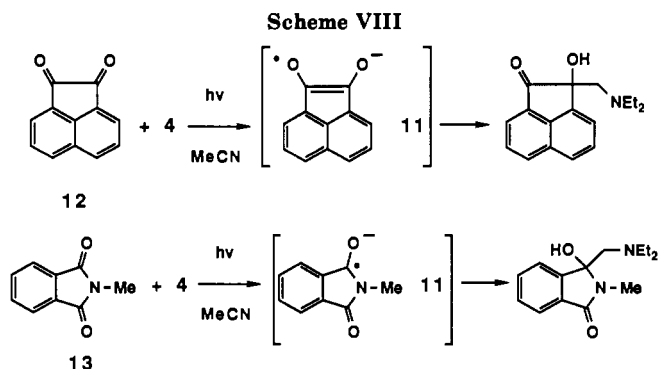
relative rates of amine cation radical 11 deprotonation and desilylation are governed by the basicity of the enone anion radicals 10. Accordingly, proton transfer from 11 to 10 in a CIRP (à la Peters) to produce the TMS adducts 8 is favored in aprotic, less silophilic media (e.g., MeCN), where the enone anion radicals should be strongly basic. In contrast, preferential generation of non-TMS adducts 9 in protic solvents (e.g., MeOH, H_2O) or when the oxophilic metal cation Li^+ is present is a consequence of the attenuated basicity of the enone anion radicals resulting from solvation (H-bonding) and coordination (Li^+) effects.

That acceptor anion radical base strength is an important factor in governing deprotonation vs desilylation rates is further evidenced by the observation that the 9:8 ratio from photoreaction of 7 (R = Me) and 4 conducted in MeOH is decreased by increases in the amine concentration (e.g., 6.51 at [4] = 0.04 M and 1.94 at [4] = 0.65 M). Thus, as the pulse radiolysis results of Das and von Sonntag[17] suggest, the tertiary amine 4 is sufficiently basic to competitively deprotonate the amine cation radical 11. Moreover, the exclusive formation of non-TMS adducts from photoadditions of silyl amine 4 to the acceptors DCA,[27] acenaphthenequinone (12),[32] and N-methylphthalimide (13)[33] in MeCN (Scheme VIII) is consistent with the proposal that the anion radical base strength plays a key role in determining the chemoselectivity of α-silyl amine cation ion radical reactions. Unlike anion radicals of enones 10 whose conjugated acids (1-hydroxyallyl radicals) have an approximate pK_a (H_2O) of 10,[34,35] those of DCA (pK_a < 0),[36] α-diketones (pK_a (H_2O) ≃ ca. 5),[34] and phthalimides (pK_a ≪ 7)[35] are more acidic, demonstrating the lowered basicity of the corresponding anion radicals.

The silyl amine cation radical fragmentation reaction has served as a key component in the design of new SET-promoted photocyclization reactions. As demonstrated by the phototransformations of the silyl (aminoethyl)cyclohexenones 14 and 15 (Scheme IX), cyclizations to give non-TMS products occur cleanly upon irradiation in MeOH while the TMS-containing products are formed exclusively when MeCN is used as solvent.[37] The much higher degree of chemoselectivity
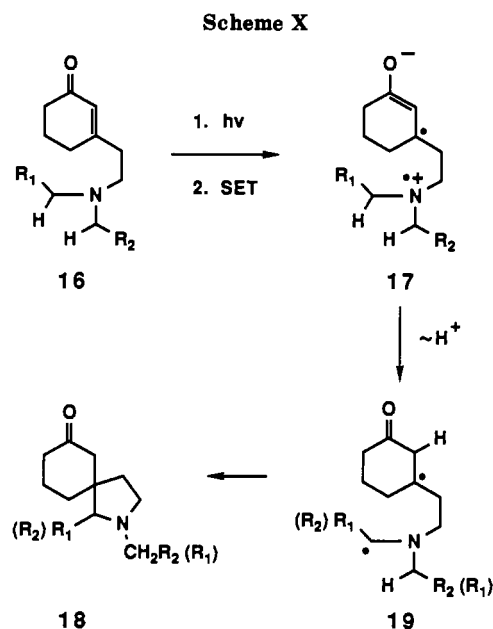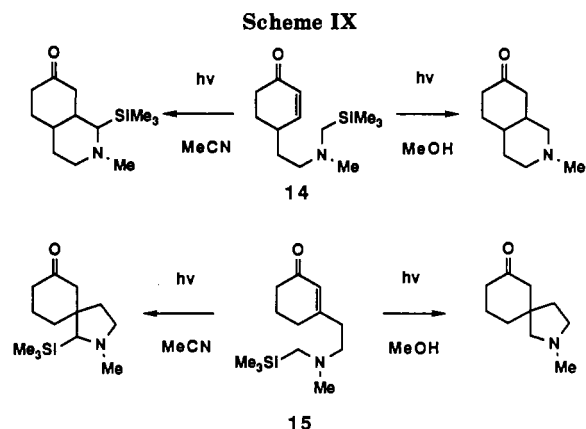
as compared to their intermolecular counterparts (e.g., 7 → 8 + 9) is due to the fact that low (ca. 1×10^{-3} M) amino–enone concentrations can be used in the intramolecular reactions.

During the course of investigations exploring the scope of the silyl amine SET photoaddition and photocyclization reactions, we noted an interesting control of carbon–carbon bond formation regiochemistry. This is exemplified in the photoadditions of silyl amine 4 to cyclohexenones 7 and photocyclizations of the silyl amino cyclohexenones 14 and 15 in MeCN, where bond formation occurs selectively at the TMS-substituted amine α-centers. These preferences reflect the relative rates of amine cation radical α-CH deprotonation and its control by substituents, an issue probed earlier by Lewis and his co-workers (see above) in their study of tertiary amine–stilbene photoadditions. If steric factors alone were responsible for governing α-CH kinetic acidities, it was not obvious why proton loss from the TMS-substituted α-carbon in the aminium radical intermediates would be faster than that at an unsubstituted methyl center. This question was addressed[37b,38] in an investigation of the photocyclization reactions of β-(aminoethyl)cyclohexenones 16 (Scheme X), where the ratio of regioisomeric products 18 reflects the relative rates of proton transfer between the aminium and

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Table II
Substituent Control of Tertiary Amine Cation Radical
Kinetic Acidities Determined through Use of the
β-(Aminoethyl)cyclohexenone Photochemical System

$$Y_2\overset{+\bullet}{N}CH_2\text{-R} \longrightarrow Y_2\overset{\bullet}{N}CH\text{-R}$$

	rel kinetic acidity			rel kinetic acidity	
R	MeCN	MeOH	R	MeCN	MeOH
H	0.01	0.01	Ph	1.0	1.0
CH$_3$	0.02	0.02	CH=CH$_2$	1.9	3.0
Si(CH$_3$)$_3$	0.1		C≡CH	3.9	2.0
CO$_2$CH$_3$	0.5	0.6			

enone anion radical centers in the intermediate zwitterionic diradicals **17**. Since the transition states for the competitive proton transfers in these reactions are similarly structured, relative kinetic acidities determined by use of this system should not be complicated by the issue of orientation of partners in ion radical pairs addressed earlier by Peters.[20] Additionally, product yields in these cyclization reactions are generally high owing to the absence of cage escape pathways which in intermolecular systems could compete with radical coupling.

As can be seen by viewing the data obtained from this study (Table II), substituents play a characteristic role in governing the relative rates of intramolecular proton transfer in the zwitterionic diradicals **17**. Alkyl substituents enhance the proton-transfer rates slightly and the TMS substituent to a greater extent, and conjugating substituents like C≡CH have the greatest effect. These results show that electronic effects can significantly contribute to α-CH kinetic acidities of tertiary aminium radicals. Stated simply, for amine cation radical α-CH deprotonation reactions leading to α-amino radicals, radical stabilizing substituents enhance reaction rates in the same way (through a control of bond dissociation energies) as they influence thermodynamic acidities (pK_a) of these radical cations.[39]

The α-Amino Radical Addition Mechanism and the Development of SET-Photosensitization Methodologies. Carbon–carbon bond formation in amine–enone photoaddition and SET-photocyclization reactions promoted by direct irradiation of the enone chromophore can occur by radical pair or diradical coupling. These pathways, depicted in Schemes VII and X, are followed when the radical intermediates are generated by proton transfer in CIRPs or zwitterionic diradicals. A mechanistic alternative involving α-amino radical conjugate addition to the α,β-unsaturated ketone moiety also appears possible when reactions take place under conditions which favor formation of SSIRP or free ion radical intermediates and where the probability of α-amino radical coupling with enone anion radicals would be low compared to the probability of their addition to ground-state enones[40] present in significantly higher concentrations.

Several observations made in our studies lend credence to this proposal. For example, irradiation of DCA in a MeCN solution containing silyl amine **4** and cyclohexenone **7** (R = CH$_3$) was found to lead to pro-

Scheme XI
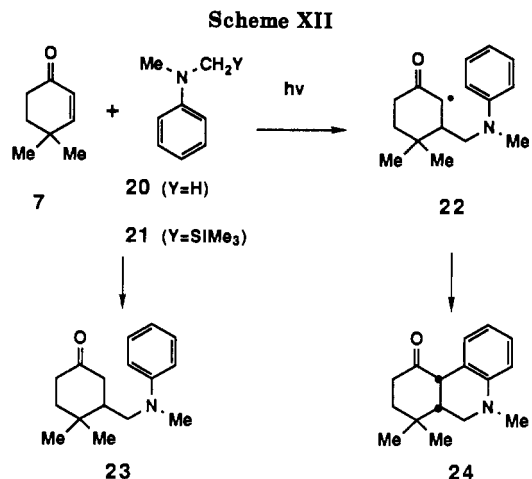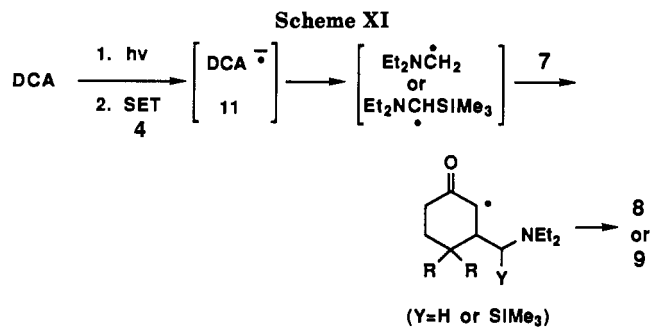
Scheme XII

duction of adducts **8** and **9** (R = CH$_3$), with the non-TMS adduct **9** becoming more predominant as the concentration of **4** is decreased. A reasonable mechanism for this DCA-photosensitized addition (Scheme XI) begins with SET from **4** to DCA[S1] and is followed by competitive desilylation/deprotonation and subsequent addition of the α-amino radicals to the enone **7**. Later studies[37b,41] have demonstrated how these reactions are terminated (see below).

Firm support for the proposed participation of radical addition pathways in the amine–enone reactions has been derived from studies probing the photoadditions of N,N-dimethylaniline (**20**) and its α-silyl analogue **21** to cyclohexenone **7** (R = CH$_3$).[42] The conceptual basis for this effort revolved about the thought that α-amino radical conjugate addition routes are distinguished by their generation of α-keto radical intermediates. Unlike the enolate anions or enols produced in radical pair coupling mechanisms, α-keto radicals (e.g., **22**) might be trapped by radical addition to appended, electron-rich π-moieties (Scheme XII). The observed formation by this trapping process of the tricyclic amino ketone **24**, along with the "normal" adduct **23** in photoreaction of **20** with **7** in MeOH, H$_2$O–MeCN, and LiClO$_4$–MeCN solutions and nearly exclusively in the DCA-sensitized addition of **21** to **7**, signals the existence of radical addition mechanisms in amine–enone and silyl amine–enone SET photoreactions.

The results presented above demonstrate that SET photosensitization can be used to promote photoreactions of silyl amine–enone systems. This method should be particularly applicable to cyclization reactions where the intramolecular radical addition pathways are en-

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Scheme XIII
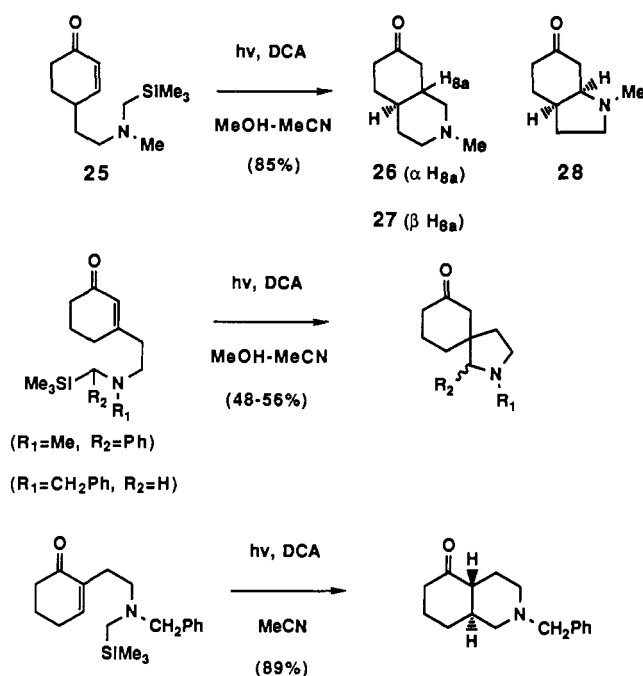
tropically favorable. Moreover, SET sensitization would be advantageous in systems where the direct irradiation method is troublesome. For example, since appropriate SET photosensitizers with long-wavelength ($\lambda > 320$ nm) absorption properties are available, formation of potentially photolabile enone excited states can be avoided. Also, the ability to select sensitizers with high excited-state reduction potentials and whose anion radicals are weakly basic extends the range of α-silyl donors that can be used in these reactions. α-Silyl amides, whose oxidation potentials are too high to readily participate in SET with triplet enones, can be oxidized by thermodynamically favored SET to singlet states of cyanoarenes like DCA.

Illustrative examples of silyl amino–enone photocyclization reactions which are promoted by the SET-sensitization methodology are shown in Scheme XIII.[37] Thus, irradiation ($\lambda > 320$ nm) of DCA in a MeCN–MeOH solution containing the silyl γ-(aminoethyl)-cyclohexenone 25 results in efficient production of the diastereomeric hydroisoquinolones 26 and 27 (ca. 6:1) along with a trace (2%) quantity of the hydroiso-indolone 28. A comparison of the stereoselectivity (6:1 cis:trans) of the DCA-sensitized photocyclization of 25 with that observed for the reaction promoted by direct irradiation of the enone in MeOH (ca. 1:1 cis:trans) demonstrates the greater degree of stereoelectronic control associated with intramolecular additions of radicals to cyclohexenones[43] than with diradical coupling processes.[44]

A wealth of information about the scope, limitations, and advantages of the SET-photosensitization methodology for silyl amine–enone cyclization has been uncovered.[37a,41] In one effort with amino ketones and amino esters having the general structure 29, we evaluated the effects of (1) incorporation of unsaturated ketone and ester functions into acyclic frameworks, (2)

tether length, (3) carbonyl type, and (4) nitrogen substituents on photocyclization reaction efficiencies. As anticipated, direct irradiation of the silyl amino ketones 30 (R = CH_3 or CH_2Ph) resulted in only cis–trans isomerization. In contrast, DCA-sensitized photoreactions of these substances in MeCN–MeOH occurred to generate the substituted piperidines 32 in high yields. Similarly, while the related esters 31 (R = CH_3 or CH_2Ph) are unreactive under direct irradiation, they undergo DCA-sensitized cyclization to form the piperidine esters 33 along with the pyrrolidine ester 34. Insight into how the sensitized cyclization processes are terminated was gained. Accordingly, production of the mono-α-deuteriated piperidinyl ester 33 in the DCA-sensitized reaction of silyl amino ester 31 (R = CH_2Ph) in CH_3OD strongly suggests that the final mechanistic step involves protonation of an enolate, produced by SET from DCA$\cdot^-$ to the α-carbonyl radical.
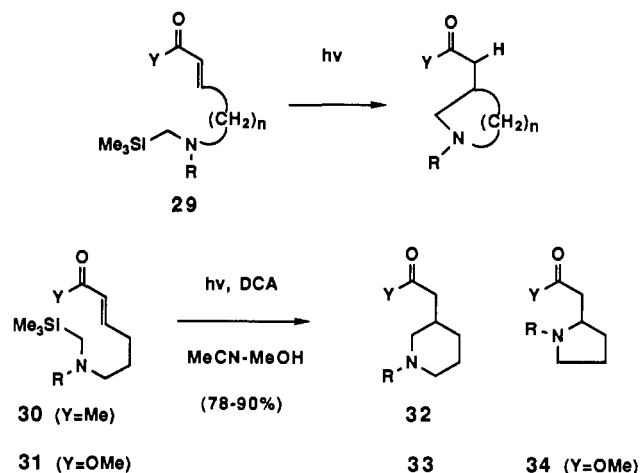
Formation of pyrrolidines (e.g., 34) in the DCA-sensitized reactions of the silyl amino esters (e.g., 31) and ketones, while only minor in the latter case, is a potentially detractive feature of this chemistry. We investigated the mechanism(s) for the competing desilylmethylation processes leading to these byproducts. Exploratory studies demonstrated that the pyrrolidine:piperidine ratio (34:33) in the DCA-sensitized photocyclization of 31 increases monotonically with increases in the DCA concentration and that pyrrolidine 34 predominates when reaction is conducted with oxygenated solutions. Thus, a likely sequence for desilylmethylation involves competitive oxidation of the intermediate α-amino radicals 35 ($E_{1/2}(+)$ = ca. -1 V)[45] by ground-state DCA ($E_{1/2}(-)$ = 0.89 V)[46] or oxygen. Hydrolysis of the resulting formaldiminium cation 36 gives the secondary amine precursor of the pyrrolidine products. The lower pyrrolidine yields in photoreactions of the unsaturated ketones vs esters probably result from the faster rates of electron rich α-amino radical additions to ketone vs ester-substituted olefins.[47]

The pathway for desilylmethylation is analogous to the familiar ECE sequences followed in two electron electrochemical oxidations of tertiary amines. Indeed anodic[48] as well as metal cation[49] (e.g., K_3FeCN_6, Hg-

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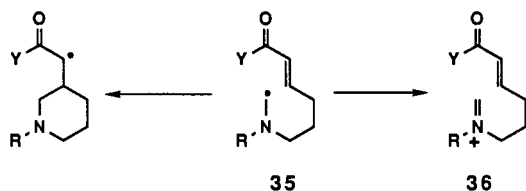
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35   **36**

(OAc)$_2$, Pb(OAc)$_4$) oxidations of the silyl amino ketones **30** and ester **31** in MeCN provide the respective pyrrolidines exclusively. (This oxidative procedure represents a useful method for generation of formaldiminium cations and, therefore, for promoting well-documented[50] iminium ion cyclization processes.)

The contrast between the DCA-sensitized and electrochemical or metal cation oxidation reactions of the silyl amino ketones and esters illustrates a unique feature of the SET-photosensitization method for initiating these α-amino radical cyclizations. Specifically, the oxidant in the photochemical procedure is the sensitizer excited state, which, owing to the low light flux employed, is present in extremely low concentrations. As a result, the excited oxidant does not promote secondary oxidation of the transient α-amino radical as is the case when alternate oxidation methods (e.g., electrochemical) are employed.

Still, oxidation of the α-amino radical intermediates by sensitizer ground states could be a major drawback of the SET-photosensitization method. A search to find ways of removing this limitation has uncovered alternate methods for performing these reactions. That ground-state DCA $(E_{1/2}(-) = -0.89$ V) can serve as an oxidant for α-amino radicals $(E_{1/2}(+) = $ ca. -1 V) makes sense from a thermodynamic viewpoint (i.e., $\Delta G°_{SET} < 0$). Other cyanoarene SET photosensitizers, such as 1,4-dicyanonaphthalene (DCN) and 1,4-dicyanobenzene (DCB), have lower ground-state reduction potentials than DCA $(E_{1/2}(-) = -1.28$ V for DCN and -1.6 V for DCB) and thus should not oxidize α-amino radicals efficiently. Verification of this proposal has come from the observations[37a,41] that the DCN-sensitized and triphenylene–DCB redox cosensitized[51] reactions of silyl amino ester **31** (R = CH$_2$Ph) give mainly the piperidine **33** along with only trace (1–2%) amounts of the pyrrolidine **34** even when the cyanoarenes are present in high concentrations. However, the overall yields of these reactions are low (29–39%) owing to other com-

petitive reactions occurring between these cyanoarenes and α-amino radicals.

A better solution to the problem involves the use of nitrogen substituents to modulate the oxidation potentials of the α-amino radical intermediates and, as a result, to reduce their oxidation rates. Owing to the effects of *N*-acyl substituents on amine oxidation potentials, the rates of oxidation by DCA of α-silyl amido and carbamido radicals should be significantly diminished while both their formation by SET to DCA^{S_1} and their additions to unsaturated ketones and esters should still be viable. This simple reasoning works well. Accordingly, the silyl carbamido ketones and esters **37** are converted to the corresponding cyclization products **38** under DCA-photosensitized conditions in high yields (ca. 90%) and to the total exclusion of products arising via desilylmethylation.

37 $\begin{cases} \text{(Y=Me or OMe)} \\ \text{(n=0 or 1)} \end{cases}$ **38**
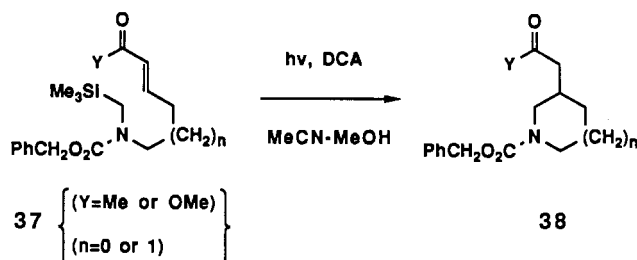
Future Directions

The radical cyclization reactions described above take advantage of several important features of SET photochemistry that have been uncovered and fully characterized in our studies and those of others. The concepts of SET photosensitization, the reactivity of silicon-substituted donor cation radicals, the control of radical cyclization vs oxidation rates, and the kinetic acidities of tertiary aminium radicals are among the issues addressed in these efforts. The level of understanding of this chemistry is now such that synthetically useful SET-promoted photochemical processes can be designed. Hopefully, our continuing studies will provide examples to demonstrate the synthetic versatility of this chemistry.

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