661 nm, $\epsilon = 365$ M^{-1} cm^{-1}; λ_{max} 518 nm, $\epsilon = 290$ M^{-1} cm^{-1}; λ_{max} 415 nm, $\epsilon = 835$ M^{-1} cm^{-1}).[13]

It is of interest to compare the structure of **3** with the analogous W(0) complex W(CO)$_3$(PCy$_3$)$_2$ (**5**) reported by Kubas and coworkers.[14] Compound **5** is a 16-electron d^6 species that exhibits an agostic interaction between the tungsten center and one of the β C–H bonds of one cyclohexyl ring. We find no evidence for such an interaction in **3**, although the structures are otherwise quite similar.[15] This is understandable since the HOMO of **3** (a$_1$ in C_{4v}, predominantly d$_{z^2}$ in character) is singly occupied, and such an interaction would lead to a 19-electron complex.

Preliminary studies of the reactivity of **3** have confirmed the previously reported observations[5] that **3** reacts rapidly with CO to give (PCy$_3$)$_2$Re$_2$(CO)$_8$ (eq 2) and with tin hydrides to afford the neutral hydride (PCy$_3$)$_2$Re(CO)$_3$H (**6**) (eq 3). In contrast to **5**, **3** reacts very slowly with H$_2$ (25 psi, benzene, 25 °C, 8 weeks).[16] The fact that this reaction proceeds so slowly is surprising since the related d^7 species Co(CN)$_5^{3-}$[17] and other transition-metal radicals[18] react rapidly with H$_2$ via so-called "homolytic" cleavage to afford metal hydrides. In the case of Co(CN)$_5^{3-}$, the results of kinetic studies are consistent with a termolecular reaction, requiring two cobalt centers in relatively close proximity.[19] The extremely bulky PCy$_3$ ligands (cone angle of 170°)[7] may impose a large steric barrier to such a reaction of **3** with H$_2$. For the related radical **4**, substituted with smaller P(*i*-Pr)$_3$ groups (cone angle of 160°),[7] the reaction with H$_2$ (25 psi, 25 °C) is complete within 3 days.

$$2\mathrm{Re(CO)_3(PCy_3)_2} + 2\mathrm{CO} \rightarrow \mathrm{Re_2(CO)_8(PCy_3)_2} \quad (2)$$

$$2\mathrm{Re(CO)_3(PCy_3)_2} + 2\mathrm{Ph_3SnH} \rightarrow \underset{\mathbf{6}}{2\mathrm{Re(CO)_3(PCy_3)_2H}} + \mathrm{Ph_3Sn{-}SnPh_3} \quad (3)$$

The synthetic methodology employed here is potentially general. In particular, the clean synthesis of radicals that are themselves photolabile is possible. We are continuing to investigate the synthesis and reactivity of radicals generated thermally from **2** and related precursors.

Acknowledgment. We thank the donors of the Petroleum Research Fund, administered by the American Chemical Society, for their support of this research. The receipt of a Cottrell Grant from the Research Corporation is gratefully acknowledged. L.S.C. is grateful for a Connecticut High Technology Graduate Scholarship.

Supplementary Material Available: Complete X-ray analysis of **3**, including summary of data collection and processing parameters, tables of positional and thermal parameters, and bond distances and angles (8 pages); tables of observed and calculated structure factors (14 pages). Ordering information is given on any current masthead page.

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(13) Previously reported UV–vis spectral data for **3**:[5] 540 nm, 665 nm $\epsilon \sim 5 \times 10^2$ M^{-1} cm^{-1}.

(14) Wasserman, H. J.; Kubas, G. J.; Ryan, R. R. *J. Am. Chem. Soc.* **1986**, *108*, 2294–2301.

(15) The shortest Re–C bond distance to a cyclohexyl ring carbon in **3** is 3.7 Å.

(16) 250-MHz ^{1}H NMR (benzene-d_6) for 6: t, −6.23 ppm, $J_{PH} = 20$ Hz.

(17) Halpern, J. *Inorg. Chem.* **1970**, *9*, 2616–2618.

(18) (a) Bercaw, J. E.; Marvich, R. H.; Bell, L. G.; Brintzinger, H. H. *J. Am. Chem. Soc.* **1972**, *94*, 1219–1238. (b) Pez, C. P.; Kwan, S. C. *J. Am. Chem. Soc.* **1976**, *98*, 8079–8083. (c) Bennett, M. A.; Patmore, P. J. *Inorg. Chem.* **1971**, *10*, 2387–2395. (d) Bonnet, J. J.; Thorez, A.; Maisonnat, A.; Galy, J.; Poilblanc, R. *J. Am. Chem. Soc.* **1979**, *101*, 5940–5949. (e) Cooley, N. A.; Watson, K. A.; Fortier, S.; Baird, M. C. *Organometallics* **1986**, *5*, 2563–2565. In contrast, there are several metal complexes that do not react readily with H$_2$: The persistent radical Mn(η^4-C$_4$H$_6$)$_2$PMe$_3$ does not react with H$_2$ (1 atm) at room temperature (Harlow, R. L.; Krusic, P. J.; McKinney, R. F.; Wreford, S. S. *Organometallics* **1982**, *1*, 1506–1513.) and Co[P(OMe)$_3$]$_4$ reacts with H$_2$ only at temperatures above 50 °C (Muetterties, E. L.; Bleeke, J. R.; Yang, Z.-Y.; Day, V. W. *J. Am. Chem. Soc.* **1982**, *104*, 2940–2942).

(19) Halpern, J. *Inorg. Chim. Acta* **1983**, *77*, L105.

Novel Electron-Transfer Photocyclization Reactions of α-Silyl Amine α,β-Unsaturated Ketone and Ester Systems

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Our studies in the area of electron transfer (SET) photochemistry have recently focused on photoaddition reactions between α-silyl amines and conjugated cyclohexenones.[3] Results from earlier efforts which demonstrate that (1) SET pathways are followed in excited state reactions between tertiary amines and cyclohexenones[4] and (2) photoinduced SET-desilylation sequences serve as selective methods for carbon–radical generation[5] have served to guide these initial studies. We have shown[3] that the tertiary silyl amine **3** photoadds to cyclohexenones **2** to yield adducts **1** and **4** in ratios that are dependent upon the reaction conditions used. In media that favor reaction via contact ion radical pairs (CIRP), TMS-adducts **4** are formed preferentially through sequential SET–proton transfer routes while non-TMS adducts **1** arising via sequential SET–desilylation paths predominate in media that favor solvent separated radical ion pair (SSIRP) formation (Scheme I). In a parallel study,[5] we noted that 9,10-dicyanoanthracene (DCA) can photosensitize additions of **3** to **2**, giving non-TMS adducts **1** predominantly by a route involving conjugate addition of an α-amino radical to the enones.

Thoughts about the synthetic potential of these processes led to an investigation of preparative and mechanistic aspects of α-silyl aminoalkyl unsaturated ketone and ester photocyclization reactions. We felt that reactions of these systems induced by direct or SET-sensitized irradiation methods could occur via respective anion diradical **5** or radical **6** cyclization modes (Scheme II). Results from this effort, reported below, have demonstrated the mechanistic and synthetic interest of these processes.

Direct irradiation[6] of cyclohexenone derivative **7**[7] in MeOH (N$_2$) leads to efficient (71%)[6] production of spirocyclic amine **8**. Also, stereoisomeric hydroisoquinolones **10** (40%) and **11** (51%) along with traces of hydroindolone **12** arise from irradiation of **9** under these conditions.[6,7] The product ratio changes in favor of **12** (34% and **10** (27%), **11** (31%)) when air-saturated solutions of **9** are directly irradiated. Photocyclizations of **7** and **9** can be SET sensitized. Thus, irradiation of DCA (8×10^{-5} M)[6] in a MeOH solution containing **7** gives **8** (78%) while **10** (71%), **11** (13%), and **12** (2%) are produced from DCA-sensitized reaction

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(3) Hasegawa, E.; Xu, W.; Mariano, P. S.; Yoon, U. C.; Kim, J. U. *J. Am. Chem. Soc.* **1988**, in press.

(4) (a) Pienta, N. J. *J. Am. Chem. Soc.* **1984**, *106*, 2704. Smith, D. W.; Pienta, N. J. *Tetrahedron Lett.* **1984**, 915. Pienta, N. J.; McKimmey, J. E. *J. Am. Chem. Soc.* **1982**, *104*, 5501. (b) Dunn, D. A.; Schuster, D. I.; Bonneau, R. *J. Am. Chem. Soc.* **1985**, *107*, 2802. Schuster, D. I.; Bonneau, R.; Dunn, D. A.; Dubien, J. J. *Ibid.* **1984**, *106*, 2706. (c) Cookson, R. C.; Hudec, J.; Mirza, N. A. *J. Chem. Soc., Chem. Commun.* **1968**, 180.

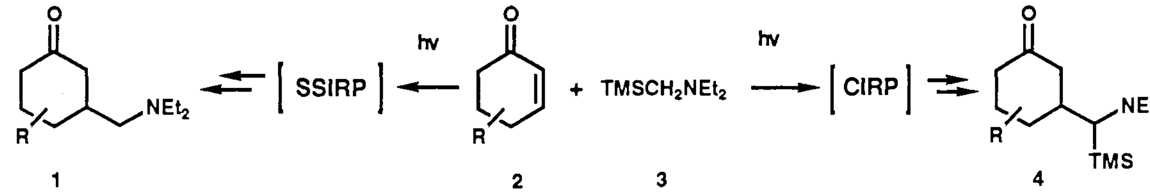
(5) (a) Ohga, K.; Yoon, U. C.; Mariano, P. S. *J. Org. Chem.* **1984**, *49*, 213. (b) Hasegawa, E.; Brumfield, M. A.; Mariano, P. S.; Yoon, U. C. *J. Org. Chem.* **1988**, in press.

(6) Irradiation conditions are as follows: uranium-filter ($\lambda > 320$ nm), N$_2$ atmosphere, [enone] and [ester] = 2×10^{-3} M, [DCA] or [DCN] = 4×10^{-4} (for sensitized reactions unless otherwise noted). Reactions were monitored by UV and GLC and conducted to >95% conversion. Product separations were by GLC or column (silica gel) chromatography. The reported yields are for isolated substances.

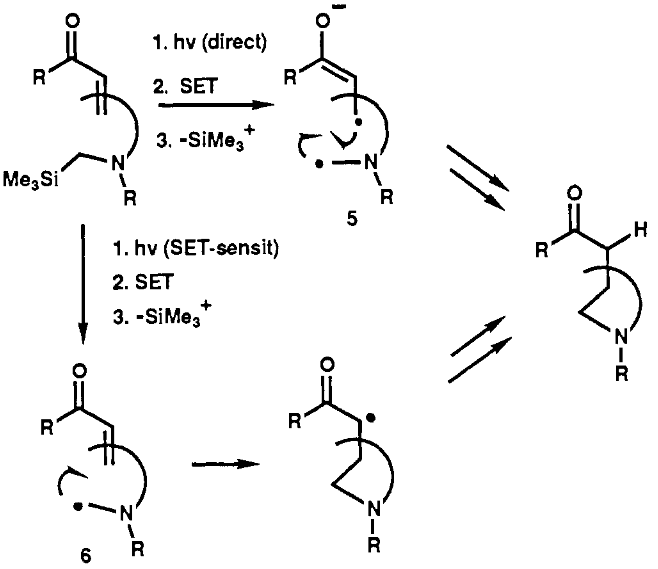
(7) Synthetic and structure and stereochemistry determination methods will be discussed in a full paper.

0002-7863/89/1511-0406$01.50/0

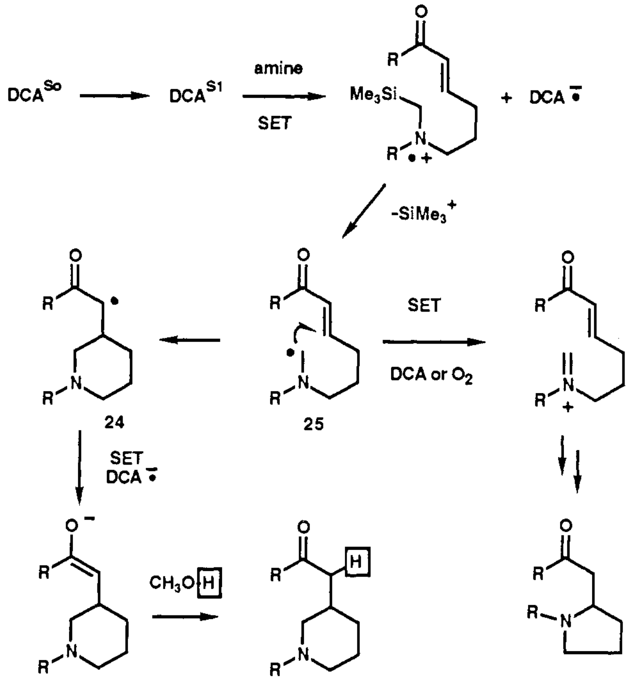
Scheme I



Scheme II



Scheme III



of 9. The relative and absolute photoproduct **10**–**12** yields from reaction of **9** are dependent upon DCA concentration (for [DCA] = 1.4×10^{-4} and 2.3×10^{-4} M, **10**, **11**, and **12** yields are 60%, 6% and 5%, and 41%, 3%, and 10%, respectively). Sensitized reaction of **9** in air-saturated MeOH–MeCN solutions gives nearly exclusively **12** (23%) and the formamide **13**. Finally efficient production of **10** and **11** occurs when 1,4-dicyanonaphthalene (DCN) is used as sensitizer even when DCN concentrations are high (e.g. for [DCN] = 4.7×10^{-3} M, **10** (71%), **11** (9%), and **12** (5%).

Additional studies have demonstrated how the SET-sensitized methodology is advantageous in promoting photocyclization of acyclic unsaturated ketone and ester systems. Accordingly, direct irradiation of the acyclic enone and acrylate derivatives **14** or **16** failed to induce formation of the piperidines **18** or **20**.[8] However, DCA-sensitized[6] reactions of **14** and its *N*-benzyl analogue **15** in 15% MeOH–MeCN occur efficiently (>90%) to produce the corresponding piperidines **18** and **19**. The related esters **16** and **17** also undergo DCA-sensitized ([DCA] = 4×10^{-4} M) photocyclization furnishing the piperidines **20** (55%) and **21** (48%) along with the respective pyrrolidines **22** (40%) and **23** (41%).[7] Interestingly, the piperidine/pyrrolidine ratios decrease with increasing DCA concentration or when oxygen is present in the photolysates.[9] Furthermore, while DCN-sensitized photocyclization of **17** is low yielding owing to competitive DCN reactions with **17**, it produces piperidine **21** (20%) and none of the homologeous pyrrolidine **23**.

Mechanistically relevant results have come from further studies. First, DCA-sensitized cyclization of **17** in 15% CH_3OD–CH_3CN leads to **21** with a single deuterium incorporated α to the ester carbonyl.[10] Secondly, GLC and UV monitoring indicates the DCA is not consumed in the sensitized reactions of enones **14** and **15**.

The observations summarized above show that these photocyclization processes serve as novel and efficient methods for N-heterocycle synthesis. The results suggest that the more versatile SET-sensitized processes follow the pathway given in Scheme III. In this route, cyclization of the α-amino radical **25** occurs to produce α-keto radical **24**. This process is competitive with oxidation of **25** ($E_{1/2(+)}$ = ca. −1.1 V)[11] by SET to DCA generating sequentially an iminium ion, a secondary amine, and the pyrrolidine product. The contribution of the latter pathway can be minimized by excluding oxygen, using low DCA concentrations or employing less easily reduced sensitizers like DCN ($E_{1/2(-)}$ = ca. −1.3 V).[12] The absence of pyrrolidine products in enone **14** and **15** sensitized photocyclization, conducted under conditions equivalent to those used for reaction of **16** and **17**, is undoubtedly due to the faster rates of α-amino radical addition to keto vs ester substituted olefins.[14] Lastly, termination of the cyclization process

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(8) Direct irradiation of acyclic enone **14** in MeOH leads to cis [illegible] is isomerization and solvent addition. The absence of photocyclization in this system suggests that intramolecular SET is non-competitive with other modes of enone excited state decay.

(9) When DCA-sensitized photolysis of **17** is conducted on an Ar-purged solution with attention being given to the rigorous exclusion of oxygen, reaction occurs to produce **21** and **23** in respective 67% and 22% yields.

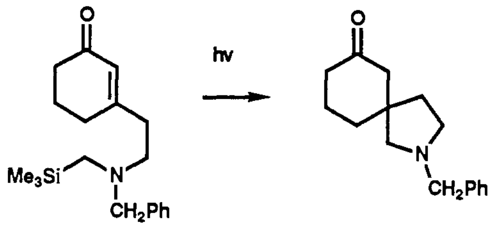
(10) In a control reaction, **21** was found not to exchange α-ester protons for deuterium when stirred in a solution of CH_3OD for extended time periods.

(11) This estimate is based upon the measured oxidation potentials of related α-amino radicals by: Wayner, D. D. M.; McPhee, D. J.; Griller, D. *J. Am. Chem. Soc.* **1988**, *110*, 132.

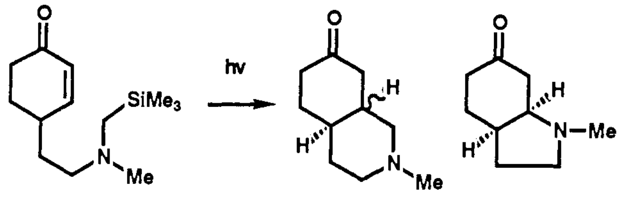
(12) (a) A summary of typical cyanoarene reduction potentials is given in: Mattes, S. L.; Farid, S. *Organic Photochemistry*; Padwa, A., Ed.; Marcel-Dekker: New York, 1983; Vol. 6, pp 233–326. (b) DCN like less conjugated cyanoarenes and unlike DCA appears to efficiently photoadd tertiary amines. For related observations see: Ohashi, M.; Myake, K.; Tsugimoto, K. *Bull. Chem. Soc. Jpn.* **1980**, *53*, 1683. Yamada, S.; Nakagawa, Y.; Watabiki, O.; Suzuki, S.; Ohashi, M. *Chem. Lett.* **1986**, 361.

(13) Reaction of α-amino radicals with O_2 can occur by routes involving hydroperoxide formation followed by solvolysis to produce iminium cations or SET ($E_{1/2(-)}$ for O_2 = ca. −0.6 V) to produce iminium cations directly. Formation of formamide **13** requires the intermediacy of an α-aminohydroperoxide which undergoes dehydration.

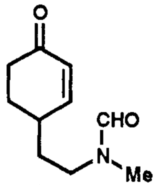
involves SET from the DCA anion radical to the α-keto radical **24** followed by enolate protonation.



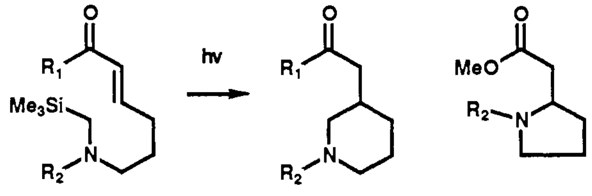
7 **8**



9 **10** (···H) **11** (—H) **12**



13



14 (R$_1$=Me,R$_2$=Me) **18** **22** (R$_2$=Me)
15 (R$_1$=Me,R$_2$=CH$_2$Ph) **19** **23** (R$_2$=CH$_2$Ph)
16 (R$_1$=OMe, R$_2$=Me) **20**
17 (R$_1$=OMe, R$_2$=CH$_2$Ph) **21**

A number of additional features of the reactions described above remain to be explored.[15] Encouragement to continue these efforts derives from the anticipated synthetic potential of these photocyclization processes.

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(14) (a) The rates of alkyl radical addition to mono-substituted alkenes depend on the nature of the alkene substituents. For example, the addition rates to $CH_2{=}CHCOCH_3$ are normally double those to $CH_2{=}CHCO_2CH_3$ (ref 14b). Importantly, simple α-amino alkyl radicals are electron rich (high-energy SOMO) and thus should add to electron poor olefins more efficiently. This should be contrasted to the chemistry of α-amido alkyl radicals which add intramolecularly to simple alkene groupings (ref 14c). (b) Giese, B. *Angew. Chem., Int. Ed. Engl.* **1983**, *764*, 763 and references therein. (c) Hart, D. J.; Tasi, Y. M. *J. Am. Chem. Soc.* **1982**, *104*, 1430. Burnett, D. A.; Choi, J. K.; Hart, D. J.; Tsai, Y. M. *Ibid.* **1984**, *106*, 8201.

(15) For example, the comparative lack of and modest stereoselectivity of the respective direct and SET-sensitized photocyclizations of **9** needs to be addressed.

Line Narrowing of Amide Proton Resonances in 2D NMR Spectra of Proteins

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Structure determination of proteins by NMR relies on the determination of through-bond (COSY-type)[1] and through-space (NOESY-type)[2] connectivities.[3] Problems in applying this strategy to proteins larger than about 15 kD arise from the increased number of resonances and the increased line width of ^{1}H resonances, resulting in severe overlap in 2D NMR spectra. Moreover, the increase in ^{1}H line width causes partial cancellation of signal within COSY-type cross multiplets, severely affecting the sensitivity associated with this crucial step in the assignment procedure. Previous attempts to narrow proton resonances by applying random[4] or complete[5] deuteriation of the nonexchangeable protons resulted in a substantial line narrowing of the remaining protons. However, this approach offers only a modest narrowing of the relatively broad amide backbone resonances.

Here, we demonstrate an alternative approach for obtaining line narrowing of the amide protons, based on the removal of the N–H heteronuclear dipolar relaxation mechanism. For both ^{14}N and ^{15}N labeled proteins, the heteronuclear dipolar coupling has a major effect on ^{1}H transverse relaxation; replacing ^{14}N by ^{15}N reduces the heteronuclear dipolar broadening contribution by only 26%.[6] This is to be contrasted with the case of small peptides, where scalar relaxation of the second kind[7] makes a major contribution to the line width of protons attached to ^{14}N.[8] Labeling with ^{15}N permits the efficient generation of heteronuclear zero- and double-quantum coherences,[9–12] which have relaxation rates that, to first order, are not affected by the heteronuclear dipolar coupling.[12,13] Hence, multiple quantum resonances can be significantly narrower than the corresponding amide ^{1}H resonances. The ^{15}N chemical shift contribution is easily removed from the multiple quantum frequency, yielding spectra that are similar in appearance to regular ^{1}H spectra, apart from line narrowing of the amide protons.

The new approach is demonstrated for the COSY experiment. The pulse scheme of this so-called pseudo-single quantum COSY (PS COSY) experiment is sketched in Figure 1. Because the pseudo-single quantum has to be present during the t_1 period, the C$^\alpha$H resonances have to be detected during t_2, necessitating the use of presaturation to suppress the H_2O resonance. To avoid excitation by the mixing pulse of H_2O that recovers during the evolution period, mixing is accomplished with a combination of selective and nonselective pulses.[14] Linearly frequency-dependent phase errors in the F_1 and F_2 dimensions, caused by the relatively long initial values of t_1 (8 ms) and t_2 (4 ms), can be calculated exactly and are easily corrected.[15]

Figure 2 shows a comparison of sections of the fingerprint (NH-C$^\alpha$H) regions of the COSY spectra of a staphylococcal nuclease/pdTp/calcium complex (18 kD). Both spectra have been recorded at 600 MHz ^{1}H frequency, with acquisition times of 74 and 100 ms in the t_1 and t_2 dimensions, respectively. Measuring times were 17 h per spectrum. Sine bell digital filtering (10° phase shifted) has been used in both dimensions, and data have been zero filled to give a digital resolution of 3.3 Hz in both dimensions. As expected, the sensitivity of the PS COSY experiment is im-

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