Experimental Section

^{1}H NMR spectra were recorded at 200 MHz in $CDCl_3$. A 9-BBN solution (0.42 M) in THF was prepared according to Brown's method.[12] 5-Decyne, 6-dodecyne, and 7-tetradecyne were prepared according to the literature.[13] Hexane and THF were dried by standard methods. All reactions were carried out under argon.

Ethyl (*E*)-3-Dodecenoate (Table I, Entry 5). To a solution of 1-decyne (1.38 g, 0.01 mol) in THF (10 mL) at 0 °C under argon was added 9-BBN in THF (11.9 mL, 0.42 M, 0.005 mol) dropwise. The reaction mixture was stirred at rt for 3 h. (When an internal alkyne in excess of 10% was used to prepare 9-alkenyl-9-BBN, the reaction was maintained at rt for at least 10 h.) In another dry flask, NaH (0.18 g, 80%, 0.006 mol) was washed with dry hexane (2 mL), and then THF (15 mL) was added under argon. The mixture of NaH and THF was cooled to 0 °C, (carbethoxymethyl)dimethylsulfonium bromide (1.37 g, 0.006 mol) was added, and the reaction mixture was stirred at 0 °C for 2 h. Then the THF solution of 9(*E*)-1′-decenyl-9-BBN was transferred into the THF solution of ethyl (dimethylsulfuranylidene)acetate at 0 °C. The reaction was allowed to continue at rt for 18 h, and then the mixture was oxidized with H_2O_2 (3 mL, 30%) and NaOAc (3 mL, 3 N) at 0 °C for 1 h. The reaction mixture was neutralized with aqueous HCl and extracted with ether, and the ethereal solution was dried over $MgSO_4$. Ethyl (*E*)-3-dodecenoate (0.9 g, 80%) was isolated by silica gel (200–300 mesh) chromatography with 9:1 petroleum:ether. The peak at 970 cm^{-1} in the IR spectrum and the coupling constant of the two vinyl protons in the ^{1}H NMR (C_6D_6, J = 15.2 Hz) spectrum of this compound clearly indicated that the compound was the *E* isomer: ^{1}H NMR ($CDCl_3$/TMS) δ 0.88 (t, 3 H, J = 6.8, CH_3), 1.28 (m, 15 H, $(CH_2)_6$, CH_3), 2.02 (br, 2 H, CH_2C=), 3.01 (d, 2 H, J = 4, *trans*-CH_2COO),[6] 4.13 (q, 2 H, J = 7.5 Hz, CH_2O), 5.53 (m, 2 H, CH=CH); ^{1}H NMR (C_6D_6/TMS) δ 0.90 (t, 3 H, J = 7.0, CH_3), 1.23 (m, 15 H, $(CH_2)_6$, CH_3), 1.94 (br, 2 H, CH_2C=), 2.91 (d, 2 H, J = 7.1, CH_2COO), 3.95 (q, 2 H, J = 7.0, CH_2O), 5.43 (dt, 1 H, J = 7.1, J = 15.2, *trans*-CH=CCOO), 5.65 (dt, 1 H, J = 7.1, J = 15.2, *trans*-C=CHCCOO), MS m/e 227 (M + 1, 100), 226 (M$^+$, 2), 180 (28), 138 (44), 55 (90), 43 (82); IR (neat) ν 1740, 1250, 970 cm^{-1}. Anal. Calcd for $C_{14}H_{26}O_2$: C, 74.21; H, 11.58. Found: C, 73.76; H, 11.60.

The following β,γ-unsaturated esters were prepared from the indicated alkyne by the procedure described above.

Ethyl (*E*)-3-heptenoate (Table I, entry 1): from 1-pentyne (1.02 g, 0.015 mol), yield 0.59 g (76%); ^{1}H NMR δ 0.89 (t, 3 H, J = 6.8), 1.26 (t, 3 H, J = 7.5), 1.34–1.48 (m, 2 H), 2.03 (br, 2 H), 3.02 (d, 2 H, J = 4), 4.14 (q, 2 H, J = 7.5), 5.54 (m, 2 H); MS m/e 157 (M + 1, 100), 156 (M$^+$, 17); IR (neat) ν 1740, 1250, 970 cm^{-1}. Anal. Calcd for $C_9H_{16}O_2$: C, 69.19; H, 10.32. Found: C, 68.80; H, 10.37.

Ethyl (*E*)-3-octenoate (Table I, entry 2): from 1-hexyne (1.23 g, 0.015 mol), yield 0.54 g (63%); n^{20}_D = 1.4356 (lit.[6] n^{20}_D = 1.4362); ^{1}H NMR δ 0.88 (t, 3 H, J = 6.8), 1.20–1.48 (m, 7 H), 2.03 (m, 2 H), 3.01 (d, 2 H, J = 4), 4.14 (q, 2 H, J = 7.5 Hz), 5.54 (m, 2 H); MS m/e 171 (M + 1, 100), 170 (M$^+$, 20); IR (neat) ν 1740, 1250, 970 cm^{-1}.

Ethyl (*E*)-3-nonenoate (Table I, entry 3): from 1-heptyne (0.96 g, 0.01 mol), yield 0.59 g (64%); ^{1}H NMR δ 0.89 (t, 3 H, J = 6.8), 1.20–1.40 (m, 9 H), 2.05 (m, 2 H), 3.01 (d, 2 H, J = 4), 4.15 (q, 2 H, J = 7.5), 5.53 (m, 2 H); MS m/e 185 (M + 1, 100), 184 (M$^+$, 18); IR (neat) ν 1740, 1250, 970 cm^{-1}. Anal. Calcd for $C_{11}H_{20}O_2$: C, 71.71; H, 10.94. Found: C, 71.61; H, 11.06.

Ethyl (*E*)-3-decenoate (Table I, entry 4): from 1-octyne (1.1 g, 0.01 mol), yield 0.61 g (62%); n^{20}_D = 1.4370 (lit.[6] n^{20}_D = 1.4372); ^{1}H NMR δ 0.88 (t, 3 H, J = 6.8), 1.20–1.40 (m, 11 H), 2.05 (m, 2 H), 3.02 (d, 2 H, J = 4), 4.15 (q, 2 H, J = 7.5 Hz), 5.51 (m, 2 H); MS m/e 199 (M + 1, 100), 198 (M$^+$, 20); IR (neat) ν 1740, 1250, 970 cm^{-1}.

Ethyl (*E*)-4-phenyl-3-butenoate (Table I, entry 6): from phenylacetylene (1.02 g, 0.01 mol), yield 0.57 g (60%); ^{1}H NMR δ 1.22 (t, 3 H, J = 7.5), 3.10 (d, 2 H, J = 5), 4.15 (q, 2 H, J = 7.5), 6.25 (m, 2 H), 7.20 (m, 5 H); MS m/e 190 (M$^+$, 43), 117 (100), 91 (23); IR neat ν 3050, 3020, 1735, 1650, 1600, 1580, 1500, 970 cm^{-1}. Anal. Calcd for $C_{12}H_{14}O_2$: C, 75.79; H, 7.37. Found: C, 75.53; H, 7.32.

Ethyl (*E*)-3-propyl-3-heptenoate (Table I, entry 7): from 4-octyne (0.61 g, 0.0055 mol), yield 0.64 g (65%); ^{1}H NMR δ 0.87 (m, 6 H), 1.20–1.42 (m, 7 H), 2.03 (m, 4 H), 2.97 (s, 2 H), 4.12 (q, 2 H, J = 7.5), 5.28 (t, 1 H, J = 7.2 Hz); MS m/e 198 (M$^+$, 30), 55 (100); IR (neat) ν 1740, 1250 cm^{-1}. Anal. Calcd for $C_{12}H_{22}O_2$: C, 72.68; H, 11.18. Found: C, 72.74; H, 11.30.

Ethyl (*E*)-3-butyl-3-octenoate (Table I, entry 8): from 5-decyne (0.78 g, 0.0055 mol), yield 0.82 g (73%); ^{1}H NMR δ 0.86 (m, 6 H), 1.20–1.40 (m, 11 H), 2.04 (m, 4 H), 2.97 (s, 2 H), 4.12 (q, 2 H, J = 7.5), 5.27 (t, 1 H, J = 7.2 Hz); MS m/e 227 (M + 1, 100), 226 (M$^+$, 19); IR (neat) ν 1740, 1250 cm^{-1}. Anal. Calcd for $C_{14}H_{26}O_2$: C, 74.29; H, 11.58. Found: C, 73.83; H, 11.80.

Ethyl (*E*)-3-pentyl-3-nonenoate (Table I, entry 9): from 6-dodecyne (0.91 g, 0.0055 mol), yield 1.0 g (80%); ^{1}H NMR δ 0.87 (m, 6 H), 1.20–1.40 (m, 15 H), 2.04 (m, 4 H), 2.97 (s, 2 H), 4.12 (q, 2 H, J = 7.5), 5.27 (t, 1 H, J = 7.2 Hz); MS m/e 254 (M$^+$, 23), 166 (97), 55 (100); IR neat ν 1740, 1250 cm^{-1}. Anal. Calcd for $C_{16}H_{32}O_2$: C, 75.53; H, 11.89. Found: C, 75.44; H, 12.00.

Ethyl (*E*)-3-hexyl-3-decenoate (Table I, entry 10): from 7-tetradecyne (1.07 g, 0.0055 mol), yield 1.0 g (71%); ^{1}H NMR δ 0.87 (m, 6 H), 1.20–1.42 (m, 19 H), 2.04 (m, 4 H), 2.96 (s, 2 H), 4.12 (q, 2 H, J = 7.5), 5.27 (t, 1 H, J = 7.2 Hz); MS m/e 283 (M + 1, 100), 282 (M$^+$, 18); IR (neat) ν 1740, 1250 cm^{-1}. Anal. Calcd for $C_{18}H_{34}O_2$: C, 76.59; H, 12.13. Found: C, 76.18; H, 12.48.

Acknowledgment. We are grateful to the National Natural Science Foundation of China and Academia Sinica for financial support for this project.

Registry No. 9(*E*)-1′-Pentenyl-9-BBN, 69322-44-7; 9(*E*)-1′-hexenyl-9-BBN, 69322-45-8; 9(*E*)-1′-heptenyl-9-BBN, 74676-16-7; 9(*E*)-1′-octenyl-9-BBN, 73062-42-7; 9(*E*)-1′-decenyl-9-BBN, 69322-46-9; 9(*E*)-1′-(2-phenylethenyl)-9-BBN, 69322-49-2; 9-(*E*)-4′-octenyl-9-BBN, 140929-39-1; 9(*Z*)-4′-octenyl-9-BBN, 105090-63-9; 9(*E*)-5′-decenyl-9-BBN, 140929-40-4; 9(*E*)-6′-dodecenyl-9-BBN, 140929-41-5; 9(*E*)-7′-tetradecenyl-9-BBN, 140929-42-6; 9-BBN, 280-64-8; $(CH_3)_2{}^+S^-CHCOOC_2H_5$, 7380-81-6; $[(CH_3)_2SCH_2COOC_2H_5]^+Br^-$, 5187-82-6; ethyl (*E*)-3-heptenoate, 54340-71-5; ethyl (*E*)-3-octenoate, 26553-47-9; ethyl (*E*)-3-nonenoate, 54211-36-8; ethyl (*E*)-3-decanoate, 82561-67-9; ethyl (*E*)-3-dodecenoate, 82561-69-1; ethyl (*Z*)-3-dodecenoate, 79837-93-7; ethyl (*E*)-4-phenyl-3-butenoate, 1205-84-1; ethyl (*E*)-3-propyl-3-heptenoate, 140929-43-7; ethyl (*Z*)-3-propyl-3-heptenoate, 141017-55-2; ethyl (*E*)-3-butyl-3-octenoate, 140929-44-8; ethyl (*E*)-3-pentyl-3-nonenoate, 140929-45-9; ethyl (*E*)-3-hexyl-3-decenoate, 51916-59-7; 1-decyne, 764-93-2; 1-pentyne, 627-19-0; 1-hexyne, 693-02-7; 1-heptyne, 628-71-7; 1-octyne, 629-05-0; phenylacetylene, 536-74-3; 4-octyne, 1942-45-6; 5-decyne, 1942-46-7; 6-dodecyne, 6975-99-1; 7-tetradecyne, 35216-11-6.

(12) Brown, H. C. *Organic Synthesis via Boranes*; Wiley-Interscience: New York, 1975; p 32.

(13) Brandsama, L. *Preparative Acetylentic Chemistry*, 2nd ed.; Elsevier Science Publisher: Amsterdam, 1988; p 55.

In Situ Generation and Utilization of Electrophilic Selenium Species ($PhSe^+$) by Photooxidative (Single Electron Transfer) Cleavage of Diphenyl Diselenide (PhSeSePh)[†,‡,1]

Ganesh Pandey* and B. B. V. Soma Sekhar

Division of Organic Chemistry (Synthesis), National Chemical Laboratory, Pune 411 008, India

Received October 22, 1991

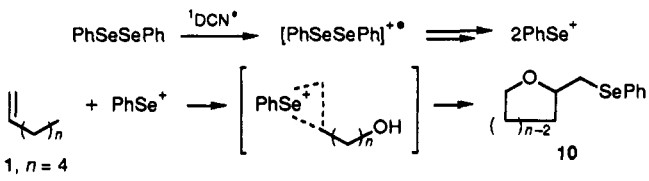
Photochemical processes operating via a single electron transfer (SET) mechanism have been attracting considerable attention owing to their mechanistic interest[2] and

[†] Respectfully dedicated to Prof. K. N. Mehrotra, Banaras Hindu University, on the occasion of his 60th birthday.

[‡] Major part of the work was carried out at IICT, Hyderabad 500 007, India.

0022-3263/92/1957-4019$03.00/0

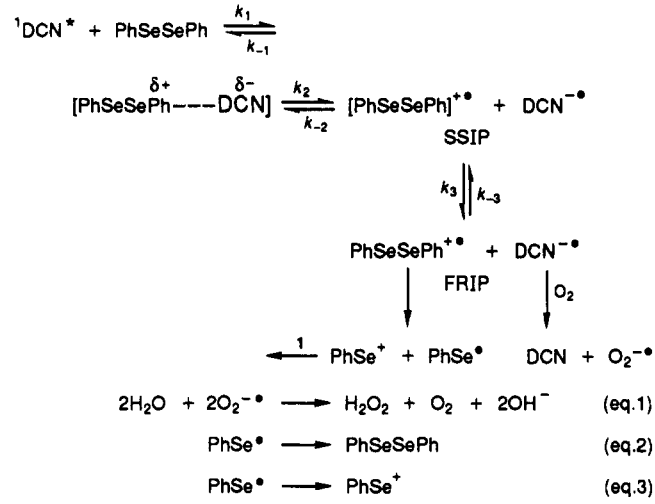
Scheme I



unique synthetic potentials.[3] Photoinduced electron transfer (PET) between ground and electronic excited states of an acceptor–donor pair results in the formation of a radical ion pair that in polar solvents diffuses apart to form free radical ions in competition with back electron transfer.[4,5] One of the most general reaction pathways available to these ion radicals is the fragmentation to ions and neutral radicals which often serve as key reactive intermediates in various synthetic reactions.[6]

Since any organic molecule with an $E_{1/2}$ for oxidation of 2.2 eV or less (vs SCE) is expected to be susceptible to oxidation via a photosensitized SET processes,[7] we undertook a study of the consequence of SET phenomenon from diphenyl diselenide (PhSeSePh),[8] using ^{1}DCN* or ^{1}DCA* as electron acceptor, with a view that [PhSeSePh]$^{+\bullet}$ formed after one-electron oxidation would undergo fast disproportionation processes, generating the electrophilic selenium species (PhSe$^+$) due to Se–Se bond (bond energy 44 kcal/mol)[9] cleavage. PhSeSePh has also been used directly in phenylselenenylation reactions employing anodic[10] and persulfate oxidation[11] procedures prior to our preliminary communication.[12] Our goal at the outset was to determine the mechanistic course of SET processes from PhSeSePh and to utilize the cleavage of resultant [PhSeSePh]$^{+\bullet}$ for the generation of PhSe$^+$ for in situ selenenylation reaction with a definite aim of replacing the conventional use of toxic and moisture-sensitive PhSeX (X = Cl, Br, OR, and NR$_2$) as the electrophilic species.[13,14]

Scheme II



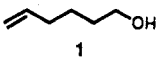
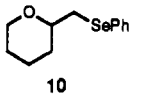
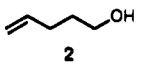
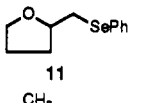
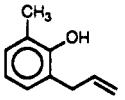
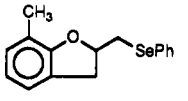
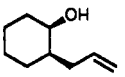
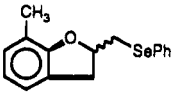
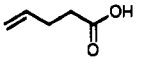
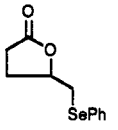
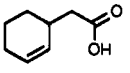
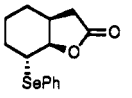
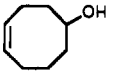
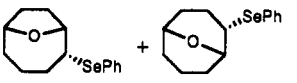
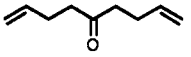
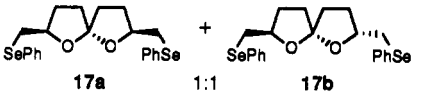
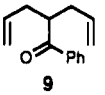
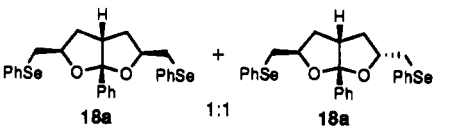
In this paper we present the details[12] of SET-initiated cleavage of PhSeSePh to electrophilic an selenium species (PhSe$^+$) using ^{1}DCN* as electron acceptor and its utilization in selenenylation reactions as depicted in Scheme I. Steady-state analysis of fluorescence quenching, dependence of the PhSeSePh quantum yield in the selenenylation reaction on its concentration, and trapping of the resultant PhSe$^+$ for synthetic purposes provides complete dissection of SET phenomenon from the above systems.

Results and Discussion

It was found that quenching of DCA (λ_{ex} = 430 nm, λ_{em} = 461 nm) and DCN (λ_{ex} = 320 nm, λ_{em} = 395 nm) fluorescence by PhSeSePh in acetonitrile at 25 °C obeys the Stern–Volmer relation. The quenching rate constants (K_q) estimated for fluorescence quenching of DCA and DCN by PhSeSePh are $(2.65 \pm 0.17) \times 10^{10}$ M^{-1} s^{-1} [15] and $(1.83 \pm 0.06) \times 10^{10}$ M^{-1} s^{-1},[16] respectively, and are close to the diffusion-controlled limit ($K_{diff} \approx 2.30 \times 10^{10}$ M^{-1} s^{-1}). Excitation and absorption spectra of DCN or DCA are unaffected in the presence of the maximum concentration of PhSeSePh. Therefore, this quenching cannot be attributed to the ground-state complexation between DCN and PhSeSePh. No exciplex emission is noticed in polar and nonpolar solvents. The ultraviolet spectra of PhSeSePh extends up to ca. 325 nm (ϵ = 200) in acetonitrile. Thus the exothermic singlet energy transfer from the excited DCN (E_s = 79.5 kcal/mol)[16] to PhSeSePh is not feasible. Furthermore, quenching due to heavy atom induced intersystem crossing could be suggested to be minimal due to a similar pattern as reported by Eaton et al.[17] for the fluorescence quenching of DCA by organotin compounds. Therefore, it is reasonable to assume that the fluorescence quenching in these cases is via a SET mechanism from the charge-transfer-stabilized exciplex. This is further supported by estimating the free energy change (ΔG_{et}) associated with this phenomenon by the Weller equation.[18] ΔG_{et} calculated by taking 1.35 eV (vs SCE) for $E_{1/2}$ oxidation for PhSeSePh, −0.89 eV for $E_{1/2}$ reduction for DCA, and 2.88 eV as $E_{0,0}$ gave an endoergic value of −14.75 kcal/mol.

(1) NCL Communication No. 5278.
(2) (a) Fox, M. A. *Adv. Photochem.* **1986**, *13*, 295. (b) Mariano, P. S. *Synthetic Organic Photochemistry*; Horspool, W. M., Ed.; Plenum Press: London, 1983; p 145. (c) Mattes, S. L.; Farid, S. *Organic Photochemistry*; Padwa, A., Ed.; Marcel Dekker: New York, 1983; Vol. 6, p 233. (d) Davidson, R. S. *Adv. Phys. Org. Chem.* **1983**, *19*, 1. (e) Kavarnos, G. J.; Turro, N. J. *Chem. Rev.* **1986**, *86*, 401. (f) Julliard, M.; Chanon, M. *Ibid.* **1983**, *83*, 425.
(3) (a) Hamada, T.; Nishida, A.; Yonemitsu, O. *J. Am. Chem. Soc.* **1986**, *108*, 140. (b) Masanovi, J.; Koholic, D. J.; Berki, R. J.; Binkley, R. W. *J. Am. Chem. Soc.* **1987**, *109*, 2851. (c) Harirchian, B.; Bauld, N. L. *J. Am. Chem. Soc.* **1989**, *111*, 1826. (d) Okada, K.; Okamoto, K.; Oda, M. *J. Am. Chem. Soc.* **1988**, *110*, 8736. (e) Kim, J.-I.; Schuster, G. B. *J. Am. Chem. Soc.* **1990**, *112*, 9635.
(4) (a) Weller, A. *Z. Phys. Chem. (Wiesbaden)* **1982**, *130*, 129. (b) Weller, A. *Ibid.* **1983**, *133*, 93.
(5) (a) Masuhara, H.; Mataga, N. *Acc. Chem. Res.* **1981**, *14*, 312. (b) Mataga, N.; Okada, T.; Kanda, Y.; Shioyama, H. *Tetrahedron* **1986**, *42*, 6143.
(6) (a) Cho, I.-S.; Tu, C. L.; Mariano, P. S. *J. Am. Chem. Soc.* **1990**, *112*, 3594. (b) Hasegawa, E.; Brumfield, M. A.; Mariano, P. S. *J. Org. Chem.* **1988**, *53*, 5435.
(7) Gassman, P. G.; Bottorff, K. J. *J. Am. Chem. Soc.* **1987**, *109*, 7547 and references cited therein.
(8) The oxidation potential of PhSeSePh was measured at 1.35 eV (vs SCE) on a cyclic voltmeter. For details, see Experimental Section.
(9) Paulmier, C. *Selenium Reagents and Intermediates in Organic Synthesis*; Pergamon Press; New York, 1986; Vol. 4, p 6.
(10) (a) Mihailovic, M. Lj.; Konstantinovic, S.; Vukicevic, R. *Tetrahedron Lett.* **1987**, *28*, 4343. (b) Konstantinovic, S.; Vukicevic, R.; Mihailovic, M. Lj. *Tetrahedrob Lett.* **1987**, *28*, 6511. (c) Vukicevic, R.; Konstantinovic, S.; Mihailovic, M. Lj. *Tetrahedron* **1991**, *47*, 859.
(11) (a) Tiecco, M.; Testaferri, L.; Tingoli, M.; Chianelli, D.; Bartoli, D. *Tetrahedron* **1988**, *44*, 2261. (b) Tiecco, M.; Testaferri, L.; Tingoli, M.; Chianelli, D.; Bartoli, D. *Tetrahedron* **1988**, *44*, 2273. (c) Tiecco, M.; Testaferri, L.; Tingoli, M.; Chianelli, D.; Bartoli, D. *Tetrahedron Lett.* **1989**, *30*, 1417.
(12) Preliminary communication: Pandey, G.; Rao, V. J.; Bhalerao, U. T. *Chem. Commun.* **1989**, 416.
(13) Nicolaou, K. C. *Tetrahedron* **1981**, *37*, 4097.
(14) Liotta, D. *Acc. Chem. Res.* **1984**, *17*, 28.
(15) DCA singlet life time was taken as 19.6 ns in acetonitrile. Mattes, S. L.; Farid, S. *J. Am. Chem. Soc.* **1983**, *105*, 1386.
(16) The singlet lifetime of DCN of 10.1 ns and the excited singlet energy were taken from the following: Arnold, D. R.; Wong, P. C.; Maroulis, A. J.; Cameron, T. S. *Pure Appl. Chem.* **1980**, *52*, 2609.
(17) Eaton, D. F. *J. Am. Chem. Soc.* **1981**, *103*, 7235.
(18) Rehm, D.; Weller, A. *Isr. J. Chem.* **1970**, *8*, 259.

Table I. Phenylselenenylation by in Situ Generated $PhSe^+$ from Photosensitized Cleavage of PhSeSePh

no	substrate[a]	irr time (h)	product[b]	yield[c] (%)
1	 1	6	 10	60
2	 2	6	 11	72
3	 3	9	 12	55
4	 4	7	 13	40[d]
5	 5	10	 14	74
6	 6	11	 15	70
7	 7	9	 16a 7:3 16b	63
8	 8	10	 17a 1:1 17b	60
9	 9	13	 18a 1:1 18a	65

[a] Preparation and characterization are given in the supplementary material. [b] 10–18 are characterized by IR, ^1H NMR, ^{13}C NMR, and mass spectra (10–16, 18, see supplementary material). [c] Isolated yields but not optimized; calculated on the basis of consumption of starting material. [d] 7:3 mixture confirmed by ^{13}C NMR; not separable by column chromatography.

The above observation suggested that $[PhSeSePh]^{+\bullet}$ formed after initial one-electron oxidation could undergo Se–Se bond cleavage, leading to the generation of $PhSe^+$ and $PhSe^\bullet$ analogous to the C–C bond dissociation reported in the case of bibenzyl radical cation.[19,20] The $PhSe^+$ generated in this manner may thus be trapped for selenenylation reaction. The above presumption was tested by irradiating a mixture of PhSeSePh (0.5 mM), 5-hexen-1-ol (1) (1.0 mM), and DCN (0.5 mM)[21] in acetonitrile by Pyrex-filtered light (>280 nm, all light absorbed by DCN only) for 6 h (till 80% of the 1 disappeared)[22] without removing the dissolved oxygen, and the usual workup and chromatographic purification (silica gel finer than 200 mesh, petroleum ether:benzene (7:3) eluent) gave **10** in 60% yield[23] (Scheme I). DCN was recovered quantitatively (98%). No other product was noticed by TLC or GC analysis of the reaction mixture. The product (**10**) gave satisfactory ^1H and ^{13}C NMR and mass spectra. No reaction is observed without the use of DCN or light. The quantum efficiency for the disappearance of PhSeSePh (Φ_{disapp}) is estimated to be 0.013 ± 0.0002 using 3.0 mM of PhSeSePh at 300 nm. These observations may be understood by considering the SET processes of PhSeSePh to $^1DCN^*$[24] as depicted in Scheme II.

The $PhSe^+$ is utilized in the selenenylation reaction[25] and $PhSe^\bullet$ is either further oxidized to $PhSe^+$ (eq 3) or dimerized to PhSeSePh (eq 2). The addition of $PhSe^\bullet$ to the olefinic double bond of 1 appears to be unreasonable not only due to its faster rate of dimerization[26] but also because the addition is a reversible process.[27] The dis-

(19) Reichel, L. W.; Griffin, G. W.; Muller, A. J.; Das, P. K.; Ege, S. *Can. J. Chem.* **1984**, *62*, 424.
(20) Davis, H. F.; Das, P. K.; Reichel, L. W.; Griffin, G. W. *J. Am. Chem. Soc.* **1984**, *106*, 6968.
(21) For preparative photochemical reactions DCN was used due to its better solubility in acetonitrile.
(22) Longer irradiation is feared to lead to a secondary ET phenomenon from the product **10** as noticed. Pandey, G.; Soma Sekhar, B. B. V.; Bhalerao, U. T. *J. Am. Chem. Soc.* **1990**, *112*, 5650.
(23) Isolated yield based on the consumption of 1.
(24) Although the triplet energy of PhSeSePh is unknown, we do not anticipate an unusually large S–T splitting in these systems. Conversely, the DCN triplet resides near 45–55 kcal/mol. So we therefore feel confident that triplet energy transfer cannot account for the chemistry we are observing.
(25) The mechanism of **10** formation is via episelenonium cation analogous to the selenoetherification mechanism reported with PhSeX (cf. ref 13).
(26) Back, T. G.; Krishna, M. V. *J. Org. Chem.* **1988**, *53*, 2533.
(27) Ito, O. *J. Am. Chem. Soc.* **1983**, *105*, 850.

solved oxygen in the solvent quenches the $DCN^{-\bullet}$ to its ground state with possible generation of $O_2^{-\bullet}$ which in aqueous solution may rapidly dismutate via hydrogen peroxide (eq 1), establishing the "true ET sensitizer" role of DCN. The above argument is supported by the observation that there is almost no reaction in the inert atmosphere and in dry acetonitrile.

A quantitative description of the above aspect is derived by correlating the fluorescence quenching and PhSeSePh disappearance quantum yield (Φ_{disapp}) dependence upon PhSeSePh concentration by a double reciprocal plot of Φ_{disapp} vs PhSeSePh concentration (Φ^{-1} vs $[Q]^{-1}$),[28] which gave an identical value ($K_{et}\tau = 107.04 \pm 10.62$) to that obtained from the Stern–Volmer fluorescence quenching analysis ($K_q\tau = 185.2 \pm 6.02$) with the limiting quantum yield ($\Phi_{lim} = 0.046 \pm 0.005$).

A number of substrates are studied and listed in Table I to determine the generality of in situ generated $PhSe^+$ in the selenenylation reaction. The in situ generated $PhSe^+$ smoothly transformed substrates **8** and **9** into an easily separable 1:1 mixture of corresponding cyclic acetals **17** and **18**. The isomers **18a** and **18b** were separated by fractional crystallization using a benzene:petroleum ether (1:9) mixture.[29] These acetals are commonly encountered moieties present in various natural products of current interest.[30,31] The stereochemistry of **18a** is assigned on the basis of the observation of five and eight carbon lines in the ^{13}C NMR spectra of **18a** (symmetrical) and **18b** (unsymmetrical), respectively, as reported previously by Mehta et al.[32] Similarly, the ^{13}C NMR spectrum of **17a** has a C_2 axis of symmetry. In contrast to isomer **17a**, **17b** showed nine lines in the ^{13}C NMR spectrum other than the aromatic signals, confirming the unsymmetrical structure of **17b**. The later assignments are also consistent with ^{13}C NMR values reported for related systems.[33]

Conclusion

In conclusion, we have successfully demonstrated the efficient SET photocleavage of stable PhSeSePh to electrophilic selenium species ($PhSe^+$) useful in a variety of selenenylation reactions. This is expected to be an alternative to the conventional electrophilic selenium reagents.

Experimental Section

General. **1**, **2**, and **5** were received from Aldrich and were used as received. DCN, DCA,[34] and PhSeSePh[35] were synthesized and purified by a reported procedure. Methanol as eluent in HPLC analysis and acetonitrile for fluorescence studies were of spectroquality (Spectrochem, India). Acetonitrile for synthesis was purified before use. Silica gel for column (finer than 200 mesh) and thin layer chromatography was obtained from Acme, India.

All nuclear magnetic resonance spectra were recorded either on Varian FT-80A or Gemini 200 spectrometers using $CDCl_3$ as solvent. All chemical shifts are reported in parts per million downfield from internal TMS; coupling constants are given in hertz. IR spectra were taken on a Perkin-Elmer Model 283B spectrometer. Mass spectra were recorded on a VG Micromass Model 7070H instrument at an ionization voltage of 70 eV. HRMS was done on the same machine. Melting points are uncorrected and recorded on the centigrade scale in an open capillary on a Campbell Electronic-Thermonik instrument.

Fluorescence spectra were recorded on a Spex fluorolog-2 spectrofluorimeter. The excitation and emission slit widths were kept at 1.5 mm. The steady-state emission spectral measurements were carried out with a 1-cm × 1-cm quartz cell. A right-angle configuration was used for excitation and emission. HPLC analysis was performed on a Shimadzu (LC-6 A system along with SPD-6A UV-variable wavelength detector with D_2 lamp and C-R3A electronic integrator) liquid chromatograph using reverse-phase C_8 (Bondapack 0.5 μm), eluting with MeOH:H_2O (9:1) degased by the freeze–thaw cycle procedure and monitoring at 254 nm.

Cyclic Voltammetry. The cyclic voltammetry experiment was carried out with a three-electrode assembly on a PAR 175 Universal Programmer and PAR RE0074 XY recorder. The cell consists of a Metro E410 hanging mercury drop electrode (HMDE) and Pt wire (auxillary electrode); the supporting electrolyte was tetraethylammonium perchlorate, and potentials are referred to SCE and uncorrected for liquid junction potential.

Fluorescence Quenching. Quenching of the DCN and DCA was carried out by using PhSeSePh as quencher. For the determination of Stern–Volmer constants K_q for DCN (2×10^{-4} M) fluorescence quenching, the intensity (I) of steady-state fluorescence at the maximum (395 nm) was measured as a function of substrate (quencher) concentration [Q] in the range 8.33×10^{-4} M to 49.98×10^{-4} M, the wavelength of excitation in these experiments was 320 nm. Linear plots were obtained on the basis of the equation $I_0/I = 1 + K_q\tau[Q]$, where I_0 denotes the fluorescence intensity in the absence of quencher. In the case of DCA (1×10^{-4} M), the excitation wavelength was fixed at 430 nm and the emission fluorescence maximum was observed at 461 nm, with quencher concentration in the range of 1×10^{-4} to 10×10^{-4} M. Stern–Volmer plots were done with use of a minimum of five quencher concentrations. No curvature was noticed in any system and intercepts were 1.00 ± 0.01 in both cases. Slopes were determined by least squares and correlation coefficients were always >0.996.

Quantum Yield Measurements. Samples for quantum yield determination were prepared by pipetting out 5 mL of the sample solution [PhSeSePh (3×10^{-3} M), **1** (6×10^{-3} M), and DCN (1.5×10^{-3} M)] into a Pyrex tube and were irradiated in a Rayonet reactor consisting of six RUL 3000-Å lamps in a merry go-round apparatus. Irradiation was carried out for a short interval of time to bring about 8–10% conversion. Uranyl oxalate actinometry was used to monitor the intensity of the excitation light.[36] Quantitative loss of PhSeSePh was carried out by HPLC. The limiting quantum yield of the reaction was measured by an inverse plot at donor concentrations of 3×10^{-3} M, 3.6×10^{-3} M, 4.2×10^{-3} M, 4.5×10^{-3} M, 5.25×10^{-3} M, and 6×10^{-3} M and substrate (**1**) concentrations of 6×10^{-3} M, 7.2×10^{-3} M, 8.4×10^{-3} M, 9×10^{-3} M, 10.50×10^{-3} M, and 12×10^{-3} M, with the DCN concentration fixed at 1.5×10^{-3} M.

General method for the photolysis is described by taking **1** as a representative example. A mixture of **1** (0.1 g, 1 mM), PhSeSePh (0.157 g, 0.5 mM), and DCN (0.045 g, 0.25 mM) in acetonitrile was irradiated in a Pyrex vessel by a 450-W Hanovia medium pressure lamp using a quartz-jacketed immersion well in combination with a Pyrex filter. The progress of the reaction was monitored by TLC. After the reaction was 80% complete, the solvent was removed by rotary evaporation under reduced pressure. The photolyte was chromatographed on silica gel using 3:7 benzene:petroleum ether as eluent, which gave **10** (0.154 g, 60% yield). DCN was recovered (~0.044 g, 98%). Selenenylated

(28) **1** was used to trap resulting $PhSe^+$ and the concentration of **1** was accordingly varied to keep the ratio of PhSeSePh and **1** constant.

(29) The isomer **18b** could not be obtained in an absolutely pure form. It was always contaminated with **18a** (≈8%, determined by ^1H NMR and by GC).

(30) (a) Kruger, G. J.; Steynn, P. S.; Vleggaar, R. J.; Rabie, C. J. *Chem. Commun.* **1979**, 441. (b) Rogers, D.; Unal, G. G.; Williams, D. J.; Ley, S. V. *Chem. Commun.* **1979**, 97. (c) Shuda, P. F. *Top. Curr. Chem.* **1980**, *91*, 75.

(31) (a) Mishima, H.; Kurabayashi, M.; Tamura, C.; Sato, S.; Kuwano, H.; Saito, A. *Tetrahedron Lett.* **1975**, 711. (b) Schonberg, G. A.; Arison, B. H.; Chabala, J. C.; Douglas, A. W.; Eskola, P.; Fisher, M. H.; Lusi, A.; Mrozi, H.; Smith, J. L.; Tolman, R. L. *J. Am. Chem. Soc.* **1981**, *103*, 4216.

(32) Mehta, G.; Rao, H. S. P.; Reddy, K. R. *Chem. Commun.* **1987**, 78.

(33) Cresp, T. M.; Probert, C.; Sondheimer, F. *Tetrahedron Lett.* **1978**, 3955.

(34) Krishna, A. "Photoinduced SET Initiated Reactions: Generation and Synthetic Applications of Arene Radical Cations"; thesis submitted to Osmania University, India.

(35) Sharpless, K. B.; Young, M. W. *J. Org. Chem.* **1975**, *40*, 947.

(36) Murov, S. L. *Handbook of Photochemistry*; Marcel Dekker; New York, 1973; p 124.

compounds were characterized by ^1H and ^{13}C NMR and mass spectral data.

17a. IR (neat, cm^{-1}): 3050, 2950, 1580, 1480, 1440, 1330, 1150, 1070, 1000, 910, 830, 680. ^1H NMR (200 MHz, $CDCl_3$): δ 7.45 (m, 4 H), 7.2 (m, 6 H), 4.3 (q, 2 H, J = 6.9 Hz), 3.05 (dd, 2 H, J = 5.8 and 12.1 Hz), 2.9 (dd, 2 H, J = 6.9 and 12.1 Hz), 2.3–2.09 (m, 2 H), 1.96 (t, 4 H, J = 7.5 Hz), 1.76–1.56 (m, 2 H). ^{13}C NMR (200 MHz, $CDCl_3$): δ 138.28, 129.97, 128.66, 126.50, 115.62, 77.00, 34.58, 32.77, 29.80. MS m/e (relative intensity): 468 [M^+, 20], 296 (20), 172 (20), 158 (20), 139 (40), 78 (100). HRMS m/e: M^+ calcd 468.0106, obsd 468.0113.

17b: IR (neat, cm^{-1}): 3050, 2950, 1580, 1480, 1440, 1330, 1150, 1070, 1000, 910, 830, 680. ^1H NMR (200 MHz, $CDCl_3$): δ 7.51 (m, 4 H), 7.25 (m, 6 H), 4.35 (q, 1 H, J = 6.8 Hz), 4.22 (q, 1 H, J = 6.9 Hz), 3.32–3.2 (dd, 1 H, J = 6.2 and 12.1 Hz), 3.1–2.9 (m, 3 H), 2.22–1.60 (m, 8 H). ^{13}C NMR (200 MHz, $CDCl_3$): δ 132.47, 130.06, 128.92, 126.70, 115.39, 79.04, 77.02, 35.85, 34.46, 32.98, 30.97, 29.98. MS m/e (relative intensity): 468 [M^+, 20], 296 (20), 172 (20), 158 (20), 139 (40), 78 (100). HRMS m/e: M^+ calcd 468.0106, obsd 468.0116.

Acknowledgment. B.B.V.S.S. thanks CSIR for financial assistance and wishes to thank Dr. M. Vairamani, IICT, Hyderabad for providing HRMS data and Dr. U. T. Bhalerao for providing all the necessary facilities.

Registry No. 1, 821-41-0; 2, 821-09-0; 3, 3354-58-3; *cis*-4, 59981-81-6; *trans*-4, 24844-28-8; 5, 591-80-0; 6, 3675-31-8; 7, 4277-34-3; 8, 74912-33-7; 9, 3462-52-0; 10, 75526-73-7; 11, 65539-72-2; 12, 71098-92-5; 13 (isomer 1), 141508-53-4; 13 (isomer 2), 141508-54-5; 14, 65234-93-7; 15, 65291-16-9; 16a, 77552-08-0; 16b, 77552-07-9; 17a, 141553-80-2; 17b, 141553-81-3; 18a, 110840-63-6; 18b, 110902-54-0; DCN, 3029-30-9; PhSeSePh, 1666-13-3; *o*-cresol, 95-48-7; allyl bromide, 106-95-6; allyl *o*-tolyl ether, 936-72-1; cyclohexanone, 108-94-1; cyclohexanone morpholine enamine, 670-80-4; morpholine, 110-91-8; 2-allyl-1-cyclohexanone, 94-66-6; 3-bromocyclohexene, 1521-51-3; diethyl malonate, 105-53-3; diethyl (2-cyclohexenyl)malonate, 6305-63-1; ethyl 2-(2-cyclohexenyl)acetate, 21331-58-8; 1,5-cyclooctadiene, 111-78-4; 5,6-epoxycyclooctene, 637-90-1; 4-bromo-1-butene, 5162-44-7; ethyl formate, 109-94-4; 5-hydroxy-1,8-nonadiene, 94427-72-2; acetophenone, 98-86-2.

Supplementary Material Available: Experimental procedures for the preparation of starting materials 3, 4, 6, 7, 8, and 9 and spectral characterization of 3–4, 6–16, and 18 by IR, ^1H NMR, ^{13}C NMR, and mass spectra, Stern–Volmer plot for quenching of DCA and DCN by PhSeSePh (Figure 1), and double reciprocal plot of Φ_{disapp} vs PhSeSePh concentration [Φ^{-1} vs $[Q]^{-1}$] (Figure 2) (10 pages). Ordering information is given on any current masthead page.

The Synthesis of 11-Cyclopropyl-5,11-dihydro-4-(hydroxymethyl)-6*H*-dipyrido[3,2-*b*:2′,3′-*e*][1,4]diazepin-6-one, a Putative Metabolite of the HIV-1 Reverse Transcriptase Inhibitor Nevirapine

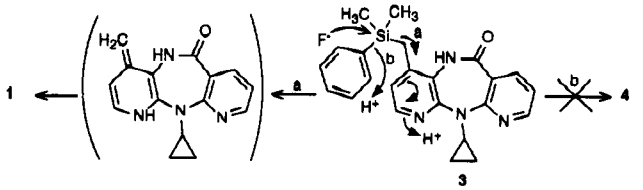
Usha R. Patel and John R. Proudfoot*

Boehringer Ingelheim Pharmaceuticals Inc., Department of Medicinal Chemistry, 900 Ridgebury Road, P.O. Box 368, Ridgefield, Connecticut 06877

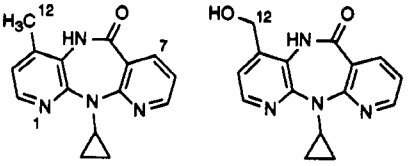
Received January 7, 1992

The dipyridodiazepinone 1 (nevirapine)[1,2] is a potent and selective noncompetitive inhibitor of HIV-1 reverse transcriptase and acts by a mechanism[3,4] distinct from that of nucleoside analogs such as AZT. It is currently undergoing clinical evaluation as a therapeutic agent against AIDS. We were interested in examining the metalation and subsequent functionalization of 1 in order to explore the chemistry of this novel tricyclic ring system, and one particular goal was the synthesis of the 12-hydroxy derivative 2 which, as a possible metabolite of 1, was required as a reference standard for metabolism studies. We expected that the 12-position of the diazepinone 1 would be susceptible to direct metalation,[5] and functionalization with a dimethylphenylsilyl group was chosen on the basis of its ready conversion to a hydroxyl group.[6]

Scheme I

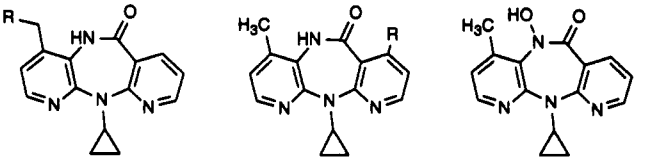


3



1 2

When the dianion of 1 was reacted with chlorodimethylphenylsilane either the 12-silyl derivative 3 or the 7-silyl derivative 5 could be obtained as the major product depending on the reaction conditions. The experimental results are presented in Table I and indicate that formation of the anion at the 7-position is kinetically favored whereas formation of the anion at the 12-position is thermodynamically favored. When all operations are carried out at <–65 °C quenching gives the 7-silyl derivative 5 in about 2:1 ratio over the 12-silyl derivative 3. At –35 °C, 5 is formed in only trace amounts, the major product being the 12-silyl derivative 3. Neither the use of a large excess of base (entries 2, 6) nor the addition of butyllithium with LDA (entry 3) or scale-up of the reaction (entry 4) noticeably affected the yields or product ratio.



3 R = $PhMe_2Si$-
4 R = FMe_2Si-
5 R = $PhMe_2Si$-
6 R = OH
7

(1) Merluzzi, V. J.; Hargrave, K. D.; Labadia, M.; Grozinger, K.; Skoog, M.; Wu, J. C.; Shih, C.-K.; Eckner, K.; Hattox, S.; Adams, J.; Rosenthal, A. S.; Faanes, R.; Eckner, R. J.; Koup, R. A.; Sullivan, J. L. *Science* **1990**, *250*, 1411.

(2) Hargrave, K. D.; Proudfoot, J. R.; Grozinger, K. G.; Cullen, E.; Kapadia, S. R.; Patel, U. R.; Fuchs, V. U.; Mauldin, S. C.; Vitous, J.; Behnke, M. L.; Klunder, J. M.; Pal, K.; Skiles, J. W.; McNeil, D. W.; Rose, J. M.; Chow, G. C.; Skoog, M. T.; Wu, J. C.; Schmidt, G.; Engel, W. W.; Eberlein, W. G.; Saboe, T. D.; Campbell, S. J.; Rosenthal, A. S.; Adams, J. *J. Med. Chem.* **1991**, *34*, 2231.

(3) Wu, J. C.; Warren, T. C.; Adams, J.; Proudfoot, J.; Skiles, J.; Raghavan, P.; Perry, C.; Potocki, I.; Farina, P. R.; Grob, P. *Biochemistry* **1991**, *30*, 2022.

(4) Cohen, K. A.; Hopkins, J.; Ingraham, R. H.; Pargellis, C.; Wu, J. C.; Palladino, D. E. H.; Kinkade, P.; Warren, T. C.; Rogers, S.; Adams, J.; Farina, P. R.; Grob, P. M. *J. Biol. Chem.* **1991**, *266*, 14670.

(5) Brandsma, L. *Preparative Polar Organometallic Chemistry 2*; Springer-Verlag: Berlin, 1990; p 136.

(6) (a) Fleming, I.; Henning, R.; Plaut, H. *J. Chem. Soc., Chem. Commun.* **1984**, 29. (b) Fleming, I.; Sanderson, P. E. J. *Tetrahedron Lett.* **1987**, *28*, 4229. (c) Colvin, E. W. *Silicon Reagents in Organic Synthesis*; Academic Press: San Diego, 1988; p 60.

0022-3263/92/1957-4023$03.00/0