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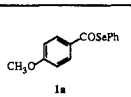
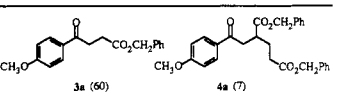
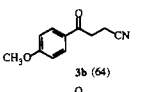
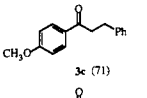
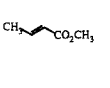
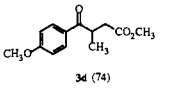
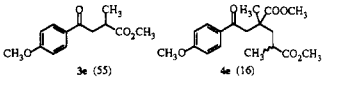
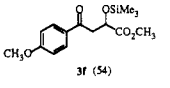
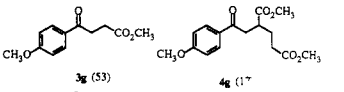
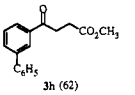
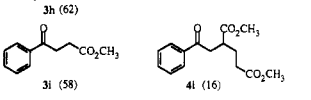
Communications

Phenyl Selenoesters as Effective Precursors of Acyl Radicals for Use in Intermolecular Alkene Addition Reactions

Summary: The scope of the use of phenyl selenoesters as effective precursors to acyl radicals for use in intermolecular olefin addition reactions is detailed.

Sir: The generation and subsequent intermolecular reaction of acyl radicals with alkenes has been long recognized as a potentially useful method of carbon–carbon bond formation since the initial report of peroxide-initiated free radical addition of aldehydes to simple olefins by Kharasch.[1] The method was subsequently extended to the use of electron-deficient alkenes,[2] alternative methods of free radical chain initiation have been described,[3] and the use of formyl derivatives[4] or acyl equivalents[3,5] has been detailed. The synthetic potential of the acyl radical as a fundamental *functionalized* free radical has renewed interest in the development of direct methods for its generation, and recent efforts have detailed the ability of acylcobalt salophen reagents[6] and *S*-acyl xanthates[7] to serve as acyl radical precursors. We recently reported that phenyl selenoesters serve as suitable precursors for the efficient generation and intramolecular cyclization (alkene addition) of acyl radicals.[8] Our interest in further defining the scope of this method of acyl radical generation provided the incentive for the study of their intermolecular

Table I. Alkene Addition Reactions of Aromatic Acyl Radicals Generated from Phenyl Selenoesters 1[a]

entry	phenyl selenoester 1[b]	alkene 2	product(s) (% yield)[c,d]
1	 1a		 3a (60) 4a (7)
2	1a		 3b (64)
3	1a		 3c (71)
4	1a		 3d (74)
5	1a		 3e (55) 4e (16)
6	1a		 3f (54)
7	1a		 3g (53) 4g (17)
8	 1b		 3h (62)
9	 1c		 3i (58) 4i (16)

[a] 5.0 equiv of **2**, 0.10 equiv of AIBN, benzene, reflux with slow addition (1 h) of 1.3 equiv of n-Bu_3SnH. [b] Full details of phenyl selenoester formation and characterization are provided in supplementary material. [c] All products exhibited ^1H NMR, IR, MS, and HRMS or C,H,N analysis consistent with the assigned structure (supplementary material). [d] All yields are based on pure material isolated by flash chromatography (SiO_2).

(1) Kharasch, M. S.; Urry, W. H.; Kuderna, B. M. *J. Org. Chem.* **1949**, *14*, 248.
(2) Patrick, T. M., Jr. *J. Org. Chem.* **1952**, *17*, 1009, 1269.
(3) (a) Photochemically initiated: Fraser-Reid, B.; Anderson, R. C.; Hicks, D. R.; Walker, D. L. *Can. J. Chem.* **1977**, *55*, 3986. (b) Low-temperature, perester-initiated: Gottschalk, P.; Neckers, D. C. *J. Org. Chem.* **1985**, *50*, 3498. (c) Self-terminating addition: Lewis, S. N.; Miller, J. J.; Winstein, S. *J. Org. Chem.* **1972**, *37*, 1478.
(4) Urry, W. H.; Huyser, E. S. *J. Am. Chem. Soc.* **1953**, *75*, 4876. Friedman, L.; Shechter, H. *Tetrahedron Lett.* **1961**, 238. Friedman, L. *J. Am. Chem. Soc.* **1964**, *86*, 1885.
(5) Barton, D. H. R.; Clive, D. L. J.; Magnus, P. D.; Smith, G. *J. Chem. Soc. C* **1971**, 2193.
(6) Coveney, D. J.; Patel, V. F.; Pattenden, G. *Tetrahedron Lett.* **1987**, *28*, 5949. Patel, V. F.; Pattenden, G. *Tetrahedron Lett.* **1988**, *29*, 707. Scheffold, R.; Orlinski, R. *J. Am. Chem. Soc.* **1983**, *105*, 7200.
(7) Delduc, P.; Tailhan, C.; Zard, S. Z. *J. Chem. Soc., Chem. Commun.* **1988**, 308.
(8) Boger, D. L.; Mathvink, R. J. *J. Org. Chem.* **1988**, *53*, 3377. See also: Crich, D.; Fortt, S. M. *Tetrahedron Lett.* **1988**, *29*, 2585; **1987**, *28*, 2895. For related intramolecular cyclization reactions of acyl radicals, see: Montheard, J. P. *C.R. Acad. Sci. Ser. C.* **1965**, *260*, 577. Čekovič, Z. *Tetrahedron Lett.* **1972**, *9*, 749. Walsh, E. J., Jr.; Messinger, J. M., II; Grudoski, D. A.; Allchin, C. A. *Tetrahedron Lett.* **1980**, *21*, 4409.

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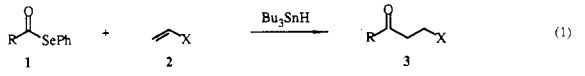
Table II. Comparison of Addition Reactions of Aromatic and Aliphatic Acyl Radicals Generated from Phenyl Selenoesters

entry	phenyl seleno-ester	alkene (equiv)	method[a]	product (% yield)[b]
1	**1a**	**2a** (5.0)	A	**3c** (71)
2	**1a**	**2a** (5.0)	B	**3c** (64)
3	**1d**	**2a** (5.0)	B	**3k** (63)[c]
4	**1d**	**2a** (2.5)	B	**3k** (55)[d]
5	**1d**	**2a** (2.5)	C	**3k** (54)[d]
6	**1e**	**2a** (2.5)	B	**3l** (51)[e]
7	**1f**	**2a** (5.0)	B	**3n** (43)[f]
8	**1a**	**2b** (5.0)	A	**3d** (74)
9	**1d**	**2b** (5.0)	A	**3j** (20)
10	**1d**	**2b** (5.0)	B	**3j** (29)
11	**1a**	**2c** (5.0)	A	**3a** (60)
12	**1e**	**2c** (5.0)	B	**3m** (46)
13	**1f**	**2c** (5.0)	A	**3o** (0)[g]

[a] Method A: 0.1 equiv of AIBN, benzene, 80 °C, slow addition (1 h) of 1.3 equiv of n-Bu_3SnH. Method B: 0.1 equiv of AIBN, 1.3 equiv of n-Bu_3SnH, benzene, 80 °C. Method C: 0.1 equiv of AIBN, 1.3 equiv of n-Bu_3SnH, benzene, 25 °C, 275-W sunlamp irradiation. [b] See footnotes *b*, *c*, and *d*, Table I. [c] Inseparable 2.3:1 mixture of mono:bis adducts. [d] 6:1 mixture of mono:bis adducts. [e] Pure monoadduct isolated by distillation. [f] 1.2:1 mixture of mono:bis adducts. [g] See text.

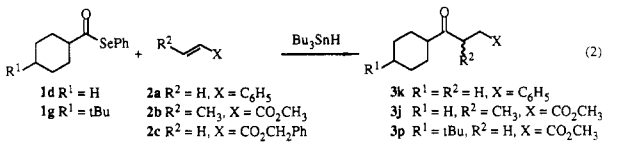
addition reactions with substituted alkenes detailed herein, eq 1.



1 2 3 (1)

In agreement with observations detailed in studies of the peroxide-initiated free radical addition of aldehydes to alkenes,[2,9] aryl acyl radicals generated through treatment of aryl phenyl selenoesters with tri-n-butyltin hydride (Table I) exhibit nucleophilic character and consequently react most productively with alkenes substituted with electron-withdrawing groups or radical-stabilizing groups (entry 3), independent of the presence of additional α- or β-substitution on the alkene component (entries 4–6). Acyl radicals generated from the substituted aryl phenyl selenoesters **1a–c** in the presence of electron-deficient olefins provided high yields (53–74%) of the intermolecular olefin addition products **3**, with little or no (0–5%) competitive reduction and with no evidence of competitive decarbonylation.[10] The most prominent competitive reaction of the aryl acyl radical addition reaction with electron-deficient olefins was the formation of small amounts (0–17%) of bis addition products **4** that were easily separated from the addition products **3** in most cases. Moreover, the tri-n-butyltin hydride mediated intermolecular alkene addition reactions of aryl phenyl selenoesters could be conducted without competitive aryl acyl radical reduction. This permitted the use of standard solution reaction conditions (method B; 1.3 equiv of n-Bu_3SnH, 0.10 equiv of AIBN, benzene, 80 °C) without resorting to conditions that minimize the effective concentration of tri-n-butyltin hydride (method A; syringe pump slow addition). The analogous reactions of aryl acyl radicals with unactivated or electron-rich alkenes provided low yields of addition products[11] accompanied by substantial amounts of direct phenyl selenoester reduction product (61–80%).

The results of the extension of the intermolecular alkene addition reactions to the use of phenyl selenoesters **1d** and **1e** and phenyl selenocarbonate **1f** (eq 2 and 3; Table II)



(2)

1d R^1 = H; **1g** R^1 = tBu

2a R^2 = H, X = C_6H_5; **2b** R^2 = CH_3, X = CO_2CH_3; **2c** R^2 = H, X = CO_2CH_2Ph

3k R^1 = R^2 = H, X = C_6H_5; **3j** R^1 = H, R^2 = CH_3, X = CO_2CH_3; **3p** R^1 = tBu, R^2 = H, X = CO_2CH_3

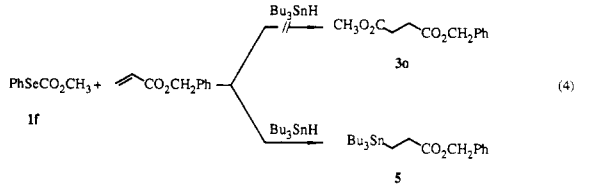
(3)

1e R^3 = CH_3; **1f** R^3 = OCH_3

2a,c

3l R^3 = CH_3, X = C_6H_5; **3m** R^3 = CH_3, X = CO_2CH_2Ph; **3n** R^3 = OCH_3, X = C_6H_5; **3o** R^3 = OCH_3, X = CO_2CH_2Ph

highlight prominent differences in the generation and reactivity of aliphatic acyl and alkoxycarbonyl radicals from those of aryl acyl radicals. Treatment of phenyl selenoesters **1d** and **1e** with tri-n-butyltin hydride in the presence of alkenes afforded the expected addition products **3** in moderate yields (29–55%) with no evidence of direct reduction. Evidently, decarbonylation and subsequent reduction is a serious competing process with secondary acyl radicals generated from aliphatic phenyl selenoesters[12,13] even when the reaction is conducted at low temperatures (25 °C) with photochemical initiation (method C; Table II, entry 5). In addition, in direct contrast to the success of the intramolecular cyclization reactions of alkoxycarbonyl radicals generated from phenyl selenocarbonates,[14] phenyl selenocarbonate **1f** displayed less propensity for participation in selective intermolecular alkene addition reactions under similar reaction conditions (Table II, entries 7 and 13). In fact, the reaction of **1f** with benzyl acrylate and tri-n-butyltin hydride afforded a 76% yield of the tri-n-butyltin addition product **5** with no evidence for formation of adduct **3o** (eq 4). Presumably



(4)

alkoxycarbonyl radical generation from **1f** is significantly slower than or different[15] from the analogous process involving treatment of phenyl selenoesters **1a–e** with tri-n-butyltin hydride.

The observations parallel the results obtained in studies of the peroxide-initiated aldehyde additions to olefins[1,2,9] and suggest that, in contrast to the intramolecular acyl radical additions to olefins,[8] secondary acyl radicals generated from aliphatic phenyl selenoesters decarbonylate at rates comparable to those of intermolecular addition to activated alkenes. In cases where decarbonylation is ex-

(9) (a) Walling, C. *Free Radicals in Solution*; John Wiley and Sons: New York, 1957; pp 273–282. (b) Walling, C.; Huyser, E. S. *Org. React.* **1963**, *13*, 91. (c) Huyser, E. S. *Free Radical Chain Reactions*; Wiley Interscience: New York, 1970; p 152. (d) Giese, B. *Angew Chem., Int. Ed. Engl.* **1983**, *22*, 753. (e) Giese, B. *Radicals in Organic Synthesis: Formation of Carbon-Carbon Bonds*; Pergamon Press: Oxford, 1986.

(10) The reaction of **1b** with n-Bu_3SnH (1.3 equiv, 80 °C, benzene, 0.05 equiv of AIBN) in the absence of alkene provided a 74% isolated yield of 3-biphenylcarboxaldehyde accompanied by 12% of biphenyl. See also: Pfenninger, J.; Heuberger, C.; Graf, W. *Helv. Chim. Acta* **1980**, *63*, 2328.

(11) The tri-n-butyltin hydride mediated reaction of **1a** with the following olefins afforded monoadducts in the designated yields: ethyl vinyl ether (18%), 1-octene (27%), allyl acetate (32%), cyclohexene (0%).

(12) The rates of decarbonylation of acyl radicals (aryl acyl ≪ primary acyl < secondary acyl radical) have been shown to differ by several orders of magnitude; see: Fischer, H.; Paul, H. *Acc. Chem. Res.* **1987**, *20*, 200 and references cited therein.

(13) Reaction of phenyl selenoester **1g** with methyl acrylate and tri-n-butyltin hydride (method A) afforded **3p** and *tert*-butylcyclohexane in a 1.4:1 ratio by GLC analysis. Adduct **3p** was isolated in 30% yield.

(14) Bachi, M. D.; Bosch, E. *Tetrahedron Lett.* **1986**, *27*, 641; **1988**, *29*, 2581. Singh, A. K.; Bakshi, R. K.; Corey, E. J. *J. Am. Chem. Soc.* **1987**, *109*, 6187. Nozaki, K.; Oshima, K.; Utimoto, K. *Tetrahedron Lett.* **1988**, *29*, 6127.

(15) Curran, D. P. *Synthesis* **1988**, 489, 417.

pectedly slower; e.g., aryl or primary acyl radicals,[12] useful yields of stoichiometric acyl radical–olefin intermolecular addition products may be obtained. Since existing methods for promoting the free radical chain addition of aldehydes to alkenes commonly employ a substantial excess (4–10 molar equiv) of aldehyde relative to alkene,[1-3] phenyl selenoesters can serve as a useful alternative and complementary source of acyl radicals in instances when this component is economically or synthetically valuable. The mild and controlled reaction conditions for acyl radical generation may permit applications in instances where the presence of sensitive functionality would prohibit the use of conventional[9] or related methodology involving ionic acyl equivalents.[16]

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Supplementary Material Available: Full details of the preparation and characterization of phenyl selenoesters 1 and the free radical addition products 3–4 (8 pages). Ordering information is given on any current masthead page.

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(16) Lever, O. W., Jr. *Tetrahedron* **1976**, *32*, 1943. Groves, J. K. *Chem. Soc. Rev.* **1972**, *1*, 73.

(17) National Institutes of Health research career development award recipient, 1983–88 (CA01136). Alfred P. Sloan Foundation research fellowship recipient, 1985–1989.

Axial Chirality by Asymmetric Induction. Diastereomeric Allene Formation via Silicon as a Chiral Auxiliary†

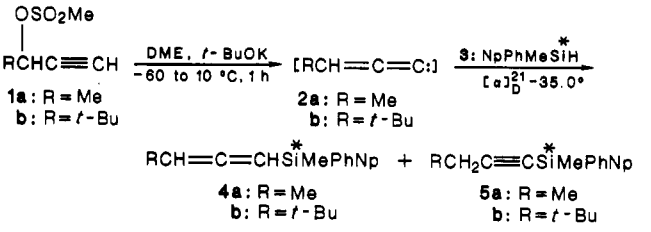
Summary: Interaction of alkenylidenecarbenes, RCH=C=C:, R = CH_3 and *t*-Bu, with chiral α-NpPhMeSi*H results in chiral allenes with a 3.5 ± 0.5% and 10.5 ± 0.5% diastereomeric excess, respectively. Hence the transfer of central chirality to axial chirality, via silicon as a chiral auxiliary, has been established. These results are discussed, and a transition state is proposed.

Sir: The practice and understanding of asymmetric synthesis is a major challenger and objective of modern organic chemistry.[2] A common means of achieving this goal is asymmetric induction via chirality transfer from one stereogenic center to another with the aid of a chiral auxiliary, most often a chiral carbon center.[2] Although numerous examples of asymmetric induction exist,[2] little, if anything, is known[3] about the possibility of generating axial chirality by way of asymmetric induction.

Silicon chemistry and its application in synthesis is burgeoning.[4] In spite of this interest and activity in silicon chemistry, the possible application of optically active organosilanes in synthesis and, especially, the use of optically active silicon as a chiral auxiliary have been rarely exploited, with only a few examples reported.[5] Hence, with the dual aim of examining the creation of axial chirality via asymmetric induction and the use of optically active silicon as the chiral auxiliary in chirality transfer, we investigated the interaction of dyssymmetrically substituted alkenylidenecarbenes **2** (Scheme I) with optically pure α-NpPhMeSi*H.[6]

Both enantiomers of optically pure α-NpPhMeSi*H are readily available by the procedure of Corriu and Moreau.[7] By a process exactly analogous to one previously reported,[8] we firmly established[1] that the insertion of $H_2C{=}C{=}C$: into the Si–H bond of optically pure (−)-(*S*)-α-NpPhMeSi*H proceeds with at least 98% stereospecificity, resulting in chiral allenylsilane of *retained* absolute con-

Scheme I



figuration with a specific rotation of $[\alpha]^{20}_D$ −6.32 ± 0.03° (pentane).

Interaction of the known methanesulfonate[9] **1** derived alkenylidenecarbenes **2** with **3** in glyme gave the silaallene

(1) Abstracted in part from: Learned, A. E. Ph.D. Dissertation, The University of Utah, 1987.

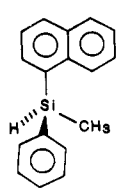
(2) *Asymmetric Synthesis*; Morrison, J. D., Ed.; Academic: New York, 1983–1985; Vols. 1–5. Nogradi, M. *Stereoselective Synthesis*; VCH Verlag: Weinheim, Germany, 1986.

(3) Jean, A.; Lequan, M. *J. Organomet. Chem.* **1973**, *50*, 75. Gibbs, R. A.; Okamura, W. H. *J. Am. Chem. Soc.* **1988**, *110*, 4062.

(4) Weber, W. P. *Silicon Reagents for Organic Synthesis*; Springer Verlag: New York, 1983. Colvin, E. *Silicon in Organic Synthesis*; Butterworths: London, 1981.

(5) Larson, G. L.; Torres, E. *J. Organomet. Chem.* **1985**, *293*, 19. Larson, G. L.; Sandoval, S.; Cartledge, F.; Fronczek, F. R. *Organometallics* **1983**, *2*, 810. Paquette, L. A.; Hathaway, S. J. *J. Org. Chem.* **1983**, *48*, 3351. Paquette, L. A; Daniels, R. G. *Organometallics* **1982**, *1*, 1449. Fristad, W. E.; Bailey, T. R.; Paquette, L. A.; Gleiter, R.; Bohm, M. C. *J. Am. Chem. Soc.* **1979**, *101*, 4420. Fry, J. L.; Adlington, M. G. *Ibid.* **1978**, *100*, 7641.

(6) (*S*)-α-NpPhMeSi*H =



(7) Corriu, R. J. P.; Moreau, J. J. E. *Bull. Soc. Chim. Fr.* **1975**, *3*, 901.

(8) Stang, P. J.; Learned, A. E. *J. Am. Chem. Soc.* **1987**, *109*, 5019.

† Dedicated to Professor Jerome A. Berson on the occasion of his 65th birthday.

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