

Radical Cyclizations of Acylgermane Oxime Ethers and Hydrazones: Direct Routes to Cyclic Hydrazones and Oximes

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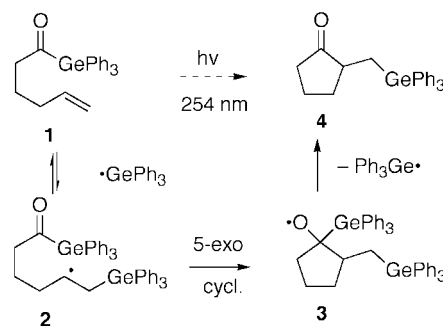
Efficient syntheses of ω -halo-, phenylseleno-, and vinylacylgermane hydrazones and oxime ethers have been developed, and the radical cyclizations of these substrates have been studied. The preparation of substituted triphenylacylgermanes has been improved through a copper-mediated coupling of acid chlorides and LiGePh_3 . Condensation of various acylgermanes with *O*-benzyl hydroxylamine or *N,N*-dimethylhydrazine efficiently generates the new acceptor systems, which undergo 5-*exo* cyclizations in good yields. The acylgermane hydrazone and -oxime ether radicals have cyclization rate constants of about 10^7 s^{-1} and are thus better acceptors than the parent acylgermanes.

Introduction

Acylgermanes¹ appear to be the best among a small number of functional groups² that can be used to directly form ketones via radical cyclizations. Following the photochemical cyclizations of unsaturated acylgermanes discovered by Kiyooka (Scheme 1, **1** \rightarrow **4**),³ Curran and Liu⁴ showed that these processes follow a unimolecular chain-transfer (UMCT) mechanism⁵ (Scheme 1). Upon irradiation, radical precursor **1** generates a germyl radical, which subsequently adds in a bimolecular fashion onto the alkene. After cyclization of the resulting secondary alkyl radical **2** onto the acylgermane, the alkoxy radical **3** rapidly collapses to a substituted ketone **4** with formation of the chain-propagating germyl radical. Even though radical cyclizations of acylarylgermanes⁶ are synthetically useful (rate constants for various 5- and 6-*exo* cyclizations are between 10^5 – 10^6 s^{-1}) and require no tin additives for initiation, bimolecular reactions⁷ with alkyl halides have only yielded products from radical recombination, rather than from a UMCT mechanism. Acylsilanes are also good radical acceptors, but despite their structural similarity to acylgermanes, they do not participate in UMCT chains and instead provide products of a radical Brook rearrangement.⁸ Ketones, in contrast, are rather poor radical acceptors, although they play important roles in powerful classes of ring-expansion reactions.⁹

Throughout the last 6 years, an assortment of radical acceptors containing carbon–nitrogen double bonds have

Scheme 1. UMCT Mechanism of Cyclization of Unsaturated Acylgermanes



been developed.¹⁰ Many of these acceptors, including imines, oximes, and hydrazones, cyclize reductively to provide products with C–N single bonds. Others, like aziridinyl imines¹¹ and azides,¹² undergo further useful transformations after cyclization. Rate data suggest that radical acceptors containing carbon–nitrogen double bonds are superior radical acceptors, often having 10–1000-fold higher cyclization rate constants than related carbon–carbon multiple-bond and carbonyl¹³ radical acceptors. In contrast, radical acceptors that directly form products containing C=N double bonds are not abundant. Nitriles are modest radical acceptors at best, and the iminyl radicals that form are prone to fragmentation.¹⁴ When cyclization does occur, the primary imine products are labile and are usually hydrolyzed in situ to form ketones. Recent advances by Kim and co-workers² with

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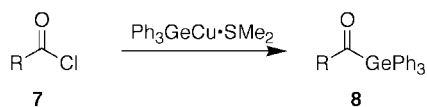
(10) Fallis, A. G.; Brinza, I. M. *Tetrahedron* **1997**, *53*, 17543–94.

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Table 1. Preparation of Acylgermanes

entry	R	acid chloride	acylgermane	yield ^a (%)
1	CH ₃	7a	8a	87
2	CH ₃ CH ₂	7b	8b	87
3	Br(CH ₂) ₄	7c	8c	61
4	CH ₂ CH(CH ₂) ₃	7d	8d	28
5	PhSe(CH ₂) ₄	7e	8e	78
6	CH ₃ (CH ₂) ₄	7f	8f	85
7	PhSeCH(CH ₃)(CH ₂) ₃	7g	8g	89

^a Isolated yields based on acid chloride.

sulfonyl oximes have provided the first direct radical routes to products containing other types of C=N double bonds.

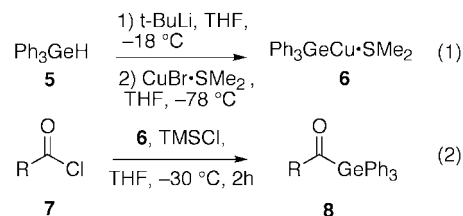
On the basis of the ample precedent of C=N multiple bonds as radical acceptors,¹⁰ we decided to study the synthesis and radical cyclizations of various C=N derivatives of acylgermanes. In this paper, we report the synthesis of new benzyl oxime ethers and dimethylhydrazones derivatives of acylgermanes. Their radical cyclizations follow a UMCT mechanism similar to that outlined in Scheme 1, and cyclization rate constants are indeed faster than for the parent acylgermanes. Moreover, we wish to report a new procedure for preparation of substituted acyltriphenylgermanes from acid chlorides.

Results and Discussion

Synthesis of Acyltriphenylgermanes. Recently, Piers¹⁵ reported a preparation of trimethylacylgermanes via the coupling of acid chlorides with a CuGeMe₃ reagent. The generality of this route was shown in eight examples, with isolated yields ranging between 82 and 92%. Piers' approach allows inclusion of chlorides, which is suggestive of functional group tolerance in the acid chloride fragment. We have found that functionalized triphenylacylgermanes are also available by the Piers route.

Generation of the new (triphenylgermyl)copper(I) reagent **6** (eq 1) was achieved by close analogy to the Piers procedure. Triphenylgermane **5**¹⁶ was lithiated in THF with *t*-BuLi at -18 °C, and the resulting lithiated germane was added to a suspension of CuBr·SMe₂ at -78 °C. The orange-yellow suspension of cuprate **6** was then reacted with a series of acid chlorides **7** (eq 2, Table 1) to give the corresponding acylgermanes **8** after aqueous workup with NH₄OH. Separation of the Cu(NH₃)₄ complex from the organic phase is facile, and the only minor impurity in the product is HGePh₃.

Table 1 shows the results of the (triphenylgermyl)copper(I) coupling reactions. The acid chlorides **7a,b,f** are commercially available, whereas all other acid chlorides were obtained from the parent acids by standard procedures. In general, all coupling reactions gave crude yields of >90%. In preparative experiments, the crude



acylgermanes were used directly in the subsequent condensation reactions. In no case did the functionality on the side chain prevent the reaction (entries 3–5, 7; Br-, PhSe-, terminal olefin). The reaction conditions have not been optimized (regarding temperature and time), but the uniformly high yields suggest that Piers' protocol is also generally suited for the preparation of triphenylacylgermanes. 5-Pentenyl triphenylacylgermane **7d** was isolated in only 28% yield, so the presence of terminal alkenes may pose some limitations. This reaction was repeated several times, but it always provided significantly lower yields than for all the other substrates.

The functional group tolerance and the availability of acid chlorides make the Piers route the method of choice for preparation of many triphenylacylgermanes. Previous preparations of functionalized acylgermanes required custom-designed procedures that introduced the radical precursor group after generating the triphenylacylgermyl moiety.¹⁷

Benzyl Oxime Ethers and Dimethylhydrazones of Acylgermanes. Condensation reactions of simple ketones with various nitrogen-nucleophiles are well-known and have been used for a long time. In contrast, acylgermanes have rarely been used in condensation reactions.¹⁸ In 1993, Ahlbrecht and Baumann¹⁹ accomplished the condensation of primary amines with acylstannanes. On the basis of these precedents, we attempted the condensation of functionalized acylgermanes with *O*-benzylhydroxylamine or *N,N*-dimethylhydrazine. As outlined in Table 2, acylgermane **8a** dissolved in CH₂Cl₂ at 25 °C and was treated either with a solution of *O*-benzylhydroxylamine²⁰ in CH₂Cl₂ or with *N,N*-dimethylhydrazine to produce acylgermane benzyl oxime ether **9a** or dimethyl hydrazone **10a** in 91% and 100% isolated yield, respectively. These derivatives were stable in open air and were handled without any special precautions. The reaction conditions were not optimized, although we found that isolated yields for *O*-benzyl oxime ethers **9** could be improved by treating the silica gel with 5% Et₃N/hexanes prior to chromatography. The varying yields reflect the fact that isolation on a smaller scale gave somewhat better results (64–92%) than on a larger scale (25–52%). The yields for dimethylhydrazones **10** became quantitative by employing an excess of dimethylhydrazine, which was removed with the solvent under vacuum. The resulting dimethylhydrazones **10** were clean and did not require further purification.

(17) Qi, H.; Curran, D. P. Acylsilicon, -germanium or boron functions. In *Compr. Org. Funct. Group Transf.*, 1st ed.; Katritzky, A. R., Meth-Cohn, O., Rees, C. W., Eds.; Elsevier Science, Inc.: New York, 1995; Vol. 4, Chapter 5.09, pp 409–433.

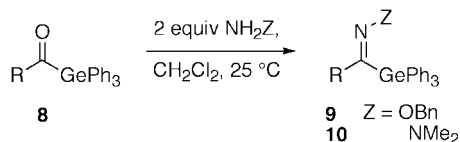
(18) Condensation of acylsilanes/germanes with tosylhydrazine: Brook, A. G.; Jones, P. F. *Can. J. Chem.* **1969**, *47*, 4353–58; only two examples of R¹COGePh₃ (R¹ = Me, Ph) were reported. Reactions with other R¹ groups failed.

(19) Ahlbrecht, H.; Baumann, V. *Synthesis* **1993**, 981–984.

(20) A catalytic amount of acid is not required, but it was essential to liberate the *O*-benzylhydroxylamine from the commercially available hydrochloride salt.

(15) Piers, E.; Lemieux, R. *Organometallics* **1995**, *14*, 5011–5012.

(16) Triphenylgermane has been prepared from PhMgBr with GeCl₄, followed by bromination and LAH reduction of Ph₃GeBr. See: Harris, D. M.; Nebergall, W. H.; Johnson, O. H. *Inorg. Synth.* **1957**, *5*, 70–72 and 76–78. We used a modification of this procedure as described in the Supporting Information.

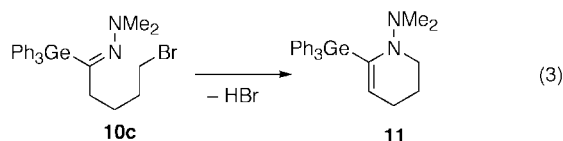
Table 2. Preparation of Acylgermane Oxime Ethers and Hydrazones

entry	R	acylgermane	C=NZ deriv (Z)	yield ^a (%)
1	CH ₃	8a	9a (OBn)	91
2	CH ₃		10a (NMe ₂)	100 ^b
3	CH ₃ CH ₂	8b	9b (OBn)	64
4	Br(CH ₂) ₄	8c	9c (OBn)	92
5	Br(CH ₂) ₄		10c (NMe ₂)	0 ^c
6	CH ₂ CH(CH ₂) ₃	8d	9d (OBn)	32
7	PhSe(CH ₂) ₄	8e	9e (OBn)	85
8	PhSe(CH ₂) ₄		10e (NMe ₂)	69, 100 ^b
9	CH ₃ (CH ₂) ₄	8f	9f (OBn)	25
10	CH ₃ (CH ₂) ₄		10f (NMe ₂)	26, 100 ^b
11	PhSeCH(CH ₃)(CH ₂) ₃	8g	9g (OBn)	52

^a Isolated yield. ^b After evaporation of hydrazine and solvent. ^c Unexpected product formed; see text.

In all the condensation reactions, only one C=N double-bond isomer of the product was formed as shown by ¹H NMR spectroscopy of the respective crude and isolated products. We tentatively concluded from NOE data (see the Supporting Information) that acylgermane oxime ethers **9a** and **9c** have the Z-configuration; however, further support for this conclusion is desirable.

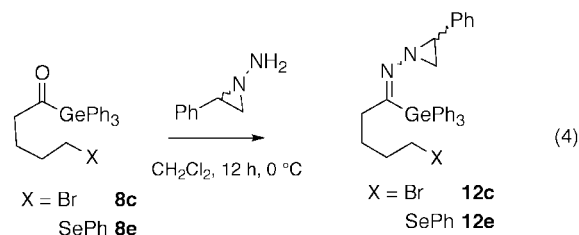
The reaction of **8c** with dimethylhydrazine did not produce the expected derivative. The isolated product was the new enamine **11** (eq 3), which suggests that hydrazone **10c** was indeed formed but underwent a subsequent ionic cyclization.²¹ Similar transformations



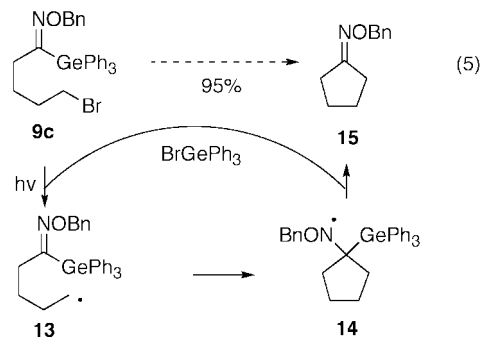
in the preparation of non-germanium-containing hydrazone radical acceptors have been observed by Kim^{1,1b,d} and Bowman.²² As far as we know, the unusual combination of functional groups in **11** has not previously been prepared.

Condensation reactions of acylgermanes with other N-nucleophiles (tosylhydrazine,¹⁸ N,N-diphenylhydrazine or benzylamine) were not successful. Using tosylhydrazine or diphenylhydrazine with **8f**, no products formed even after 2 months, while reaction with stoichiometric amounts of benzylamine and **8f** led to an inseparable 1:2 mixture of E/Z isomers. Condensation of acylgermane **8c** or **8e** with 1-amino-2-phenylaziridine successfully led to acylgermane aziridinyliimines **12c** and **12e** (eq 4). Unfortunately, these interesting products did not react smoothly under typical radical conditions.¹¹

Radical Chemistry of Acylgermane Oxime Ethers and Hydrazones. The radical chemistry of the novel acylgermane oxime ethers **9** and hydrazones **10** has been successfully developed and presents a useful extension



to the known class of acylgermanium radical acceptors. In a typical experiment (eq 5), a solution of radical



precursor **9c** in a small amount of benzene was irradiated (254 nm) in a quartz vessel for 90 min at 25 °C. Thin-layer chromatographic analysis of the crude reaction mixture revealed only two spots, which were shown to be cyclopentanone O-benzyl oxime ether **15** and Ph₃GeBr. After the usual workup and chromatographic purification, oxime **15** was isolated in 95% yield. When the reaction was run in benzene-d₆ in a sealed quartz NMR tube, the NMR spectrum taken after 90 min of irradiation did not show any signals for the starting material **9c** or side products. This method is very attractive because the cyclization is clean and efficient and because the reaction requires no initiator other than UV light and thus avoids toxic tin additives. We assume that the mechanism in eq 5 is operating, and this mechanism is analogous to the one described for cyclization of ω-haloacylgermanes.¹

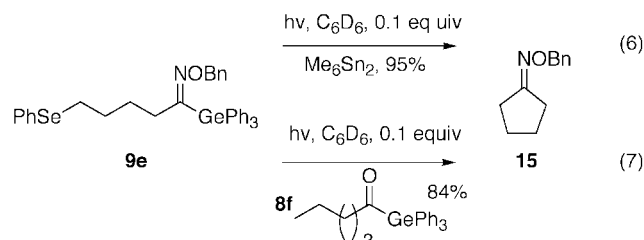
Strikingly, **9d** and the PhSe-containing precursors **9e,g** and **10e** did not undergo this cyclization upon photolytic initiation.²³ For example, irradiating **9e** for up to 8 h at 254 nm at 25 °C produced a small amount of a terminal alkene (~5–8%) along with unchanged starting material **9e**. These failures suggested that both the C=N and the PhSe–C bond resist cleavage under photolytic conditions, so that the chain is not initiated. In contrast, PhSe-bearing acylgermane **8e** quantitatively cyclized to cyclopentanone on irradiation,¹ which is consistent with the postulate that chains are initiated by Norrish-type I photocleavage of the acylgermane.

To overcome the lack of reactivity of nonhalide substrates under photoinitiation conditions, two different methods were developed (eqs 6 and 7). In the first, irradiation of **9e** under the usual conditions in the presence of 0.1 equiv of Me₆Sn₂ provided **15** in 95% yield. In the second, irradiation of **9e** in the presence of 0.1 equiv of acetyltriphenylgermane **8f** led to **15** in 84% yield.

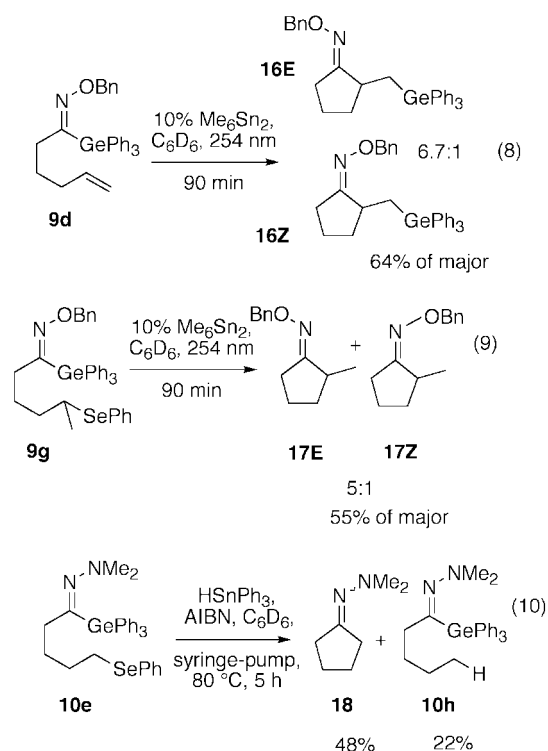
(21) Similar reactivities have been observed with suitably substituted acylgermanes; see ref 6a and: Tsai, Y. M.; Niel, H. C.; Cherng, C. D. *J. Org. Chem.* **1992**, *57*, 7010–14.

(22) Bowman, W. R.; Stephenson, P. T.; Terrett, N. K.; Young, A. R. *Tetrahedron* **1995**, *51*, 7959–7980.

(23) Ionic vs radical behavior of selenides and sulfides: Kropp, P. J.; Fryxell, G. E.; Tubergen, M. W.; Hager, M. W.; Harris, G. D., Jr.; McDermott, T. P., Jr.; Tornero-Velez, R. *J. Am. Chem. Soc.* **1991**, *113*, 7300–7310.



The initiation procedure with Me_6Sn_2 was extended to the cyclization of **9d** and **9g**, while precursor **10e** was cyclized with a syringe-pump-added solution of AIBN/ HSnPh_3 (5 h at 80°C). ^1H NMR spectroscopy confirmed for the first two cases (eqs 8 and 9) that the starting material was consumed and that the corresponding cyclized product was formed. Products **16** and **17** were formed as 6.7/1 and 5/1 mixtures of *E/Z* double-bond isomers. The major isomers were isolated in good yields (64% for **16E**, 55% for **17E**), while **18** was obtained in only 48% yield (eq 10) due to competitive reduction of the starting material (22% **10h**).



The stereochemical assignment of isomeric products **16E/Z** and **17E/Z** was accomplished by NMR spectroscopy. The ^{13}C -DEPT NMR spectra of isomers **17E/Z** differed only in the aliphatic CH - and $\text{CH}_2\text{C}=\text{N}$ resonances. According to ample precedent in the literature,²⁴ we assigned the *E* geometry to the compound with the more downfield CH shift (38.0 ppm) and the *Z* geometry to the compound with the more upfield CH shift (35.0 ppm).

The oximes **17E/Z** produced in the radical cyclization were identical to authentic samples made from 2-methyl-

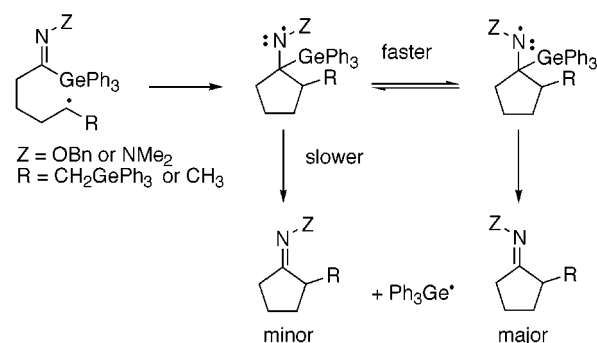


Figure 1. Rationale for Stereoselection

Table 3. Cyclization Rate Constant (80°C) for **9c**

entry	[15/9h] ^a	$[\text{HSnPh}_3]_{\text{effc}}$ ($\text{mol}\cdot\text{L}^{-1}$)	k_c (80°C) (s^{-1})
1	6.63	0.14	2.32×10^7
2	4.60	0.27	3.11×10^7
3	3.19	0.33	2.63×10^7
4	1.15	0.85	2.44×10^7
5	1.11	0.99	2.75×10^7

^a Ratio was obtained from ^1H NMR integration of crude reaction mixture.

cyclopentanone. This reaction provided a 3/1 mixture of *E/Z* isomers, and we believe that this is the thermodynamic ratio. Thus, although we cannot rule out partial isomerization of the oximes under the radical conditions, the nonequilibrium (5/1) ratio obtained in the cyclization of **9g** clearly shows that the radical reaction is under kinetic control. Radical addition/elimination reactions of alkenes often proceed with some degree of retention when the elimination step is sufficiently rapid.^{25,26} Assuming that the stereochemical assignments of the precursors are correct, the cyclizations of **9d** and **9g** proceed not with retention but with predominant inversion. This suggests that bond rotation of the intermediate radicals formed on cyclization is faster than elimination of the triphenylgermyl radical, as shown in Figure 1.

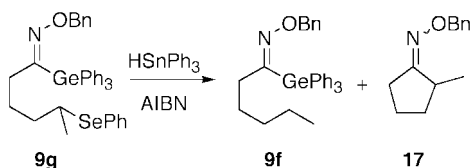
Rate Constants for 5-Exo Cyclization. The 5-*exo* cyclization rate constants of radicals generated from **9c,g** and **10e** were measured by standard competition experiments (tin hydride method) at several different concentrations.²⁷ In a typical experiment, 1 equiv of the radical precursor (**9c,g** or **10e**) was reacted with a catalytic amount of AIBN and 3 equiv of HSnPh_3 (0.1–0.9 M, see Tables 3–5) in benzene- d_6 at 80°C for 2 h. Direct ^1H NMR integration of the benzylic methylene singlets for *O*-benzyloxime ethers (or of the *N*-methyl singlets for dimethylhydrazones) provided the ratio of cyclized to reduced products and established that all starting material was consumed. Inspection of the crude ^1H NMR

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(26) (a) Russell, G. A.; Ngoviwatthai, P.; Tashtoush, H. I. *Organometallics* **1988**, *7*, 696–702. (b) Lowinger, T. B.; Weiler, L. *J. Org. Chem.* **1992**, *57*, 6099–6101.

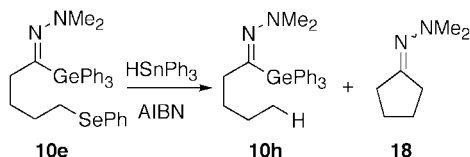
(27) Newcomb, M. *Tetrahedron* **1993**, *49*, 1151–1176.

(24) Configurational assignment of hydrazone/oxime double bond isomers: (a) Duddeck, H. *Stereoselective Synthesis. Methods of Organic Chemistry (Houben-Weyl)*; Helmchen, G., Hoffmann, R. W., Mulzer, J., Schaumann, E., Eds.; Thieme: New York, 1995; Vol. E21a, pp 324–327. (b) Bunnell, C. A.; Fuchs, P. L. *J. Org. Chem.* **1977**, *42*, 2614–2617.

Table 4. Cyclization Rate Constant (80 °C) for 9g

entry	[17/9f] ^a	[HSnPh ₃] _{eff} (mol·L ⁻¹)	k _c (80 °C) (s ⁻¹)
1	2.24	0.25	1.40 × 10 ⁷
2	1.87	0.32	1.50 × 10 ⁷
3	1.50	0.45	1.69 × 10 ⁷

^a Ratio was obtained from ¹H NMR integration of crude reaction mixture.

Table 5. Cyclization Rate Constant (80 °C) for 10e

entry	[18/10h] ^a	[HSnPh ₃] _{eff} (mol·L ⁻¹)	k _c (80 °C) (s ⁻¹)
1	0.88	0.15	2.84 × 10 ⁶
2	0.42	0.22	2.31 × 10 ⁶
3	0.29	0.31	2.25 × 10 ⁶
4	0.10	0.77	1.93 × 10 ⁶

^a Ratio was obtained from ¹H NMR integration of crude reaction mixture.

spectra also revealed that Ph₃GeH was formed during the course of the reaction.²⁸ This is presumably formed by the reaction of Ph₃Ge[•] with Ph₃SnH.²⁹ However, since Ph₃GeH is a poorer hydrogen donor than Ph₃SnH and is present in lower concentration, we decided not to compensate for its presence. All other products were stable under the reaction conditions as shown in control experiments. Reactions were only conducted once or twice for each concentration because each derivative gave reproducible rate constants within experimental error.

The primary derivative **9c** has a cyclization rate constant of about 2.3 × 10⁷ s⁻¹ (±0.3 × 10⁷ s⁻¹, 80 °C), while secondary derivative **9g** has a slightly lower rate constant of about 1.4 × 10⁷ s⁻¹ (±0.1 × 10⁷ s⁻¹, 80 °C). On the other hand, dimethylhydrazone derivative **10e** [2.1 × 10⁶ s⁻¹ (±0.3 × 10⁶ s⁻¹, 80 °C)] is about 10 times less reactive than **9c**, which is in accord with HOMO–LUMO considerations.³⁰ As was previously shown for acylgermanes,¹ substituents lowering the LUMO energy of the carbonyl group will accelerate cyclization. These cyclization rate constants are two to three times higher than for the parent acyltriphenylgermane radicals (primary pentenylacyltriphenylgermane radical.^{6b} 7 × 10⁶

(28) The formation of Ph₃GeH presumably also occurred in previously reported kinetic experiments (see ref 1).

(29) (a) Zavitsas, A. A.; Chatgililoglu, C. *J. Am. Chem. Soc.* **1995**, *117*, 10645–49. (b) Reaction of triphenylgermanium bromide and AIBN with triphenyltin hydride provides triphenylgermanium hydride and triphenyltin bromide.

(30) MO calculations were performed for two model compounds on a Silicon Graphics Indy R4600, running Spartan SGI 4.0.3c GL. Orbital energies and Mulliken charges were calculated after geometry optimization at the AM1 level, employing the Hartree–Fock procedure without solvent: CH₂=NNMe₂ (HOMO–8.5545 eV, LUMO 1.6685 eV), CH₂=NOBn (HOMO–9.6920 eV, LUMO 0.2470 eV).

s⁻¹, 80 °C; secondary hexenylacyltriphenylgermane radical: 1.5 × 10⁶ s⁻¹, 80 °C).

Conclusions

We have developed two new radical acceptor systems, acylgermane benzyloxime ethers and dimethylhydrazones, which were obtained as single *Z* isomers in yields of 65–100% by condensation of *N*-nucleophiles with acylgermanes. The required triphenylacylgermane precursors were generated by a copper-mediated coupling of acid chlorides and LiGePh₃, based on prior work from Piers. The significant advantages of the copper-mediated preparation over previously used methods (experimental simplicity, yield, purity, generality, cost) make this the method of choice for the future, especially in view of the inherent convergency: the side chain with the radical precursor can be independently synthesized and then converted to an acylgermane at a late stage.

Like the related acylgermanes, the acylgermane oxime ethers and hydrazones are excellent radical acceptors. Simple irradiation (254 nm) provides efficient initiation for bromides, but fails for PhSe-radical precursors. This problem can be overcome by adding ditiin or a simple (noncyclizable) acylgermane to facilitate initiation. 5-*Exo* cyclizations were successfully studied for three compounds, with rate constants roughly three times higher than for the parent acylgermanes. A synthetically attractive feature is that cyclization products retain a C=N bond.

Experimental Section

General Methods. All glassware was dried in an oven at 140 °C prior to use. All experiments were conducted under an atmosphere of dry argon unless indicated otherwise. Solvents were dried as follows: Methylene chloride was distilled from CaH₂; diethyl ether, THF, and benzene were distilled from sodium/benzophenone; toluene was distilled from sodium, pyridine from KOH and stored over KOH. All NMR spectra were recorded on a Bruker AC-300 or DPX-300 (¹H: 300 MHz, ¹³C: 75 MHz) or a Bruker DPX-500 (¹H: 500 MHz, ¹³C: 125 MHz) NMR spectrometer at ambient temperatures. Column chromatography (low-pressure chromatography) was performed with ICN silica gel 60 (230–400 mesh). Thin-layer chromatography (TLC) was carried out on Merck silica gel 60 F-254 glass-backed plates. TLC visualization was accomplished via UV-quenching (254 nm) and potassium permanganate or sulfo molybdic acid staining solution. Please refer to the Supporting Information for further details and full compound characterization.

General Procedure for the Preparation of Acylgermanes.¹⁵ A suspension of CuBr·SMe₂ (762 mg, 3.70 mmol) in dry THF (18 mL) was cooled to –78 °C for 40 min. In a second flask, *t*-BuLi (1.7 M in pentane, 2.15 mL, 3.66 mmol) was added to a precooled (–18 °C) solution of HGePh₃ (1.233 g, 4.04 mmol) in THF (5 mL). This solution was stirred for 10 min at –15 °C and then cannulated into the copper salt suspension, which turned bright yellow. The resulting mixture was stirred for 1 h at –78 °C. To the now orange suspension was added trimethylchlorosilane (0.28 mL, 2.21 mmol); after 5 min, the respective acid chloride (either as solution in THF or neat, 2.33 mmol) was added and the mixture was kept at –78 °C for 1 h. The amber suspension was then warmed to –30 °C and kept at this temperature for 2 h (black solution). The cuprate was then quenched by pouring it into a 1:1 mixture of Et₂O (25 mL) and an aqueous solution of NH₄OH/NH₄Cl (sat.) of pH 8–9 (25 mL). After the mixture was stirred for 1–2 h, the two phases were separated; extraction of the blue aqueous layer (3 × Et₂O) and washing of the combined organic layers (2 × H₂O, 2 × brine) was followed by drying

over MgSO_4 and concentration in vacuo. The solid acylgermanes were obtained almost pure; the only trace impurity was HGePh_3 ($R_f = 0.57$ (5% $\text{Et}_2\text{O}/\text{hexane}$), which was removed by column chromatography. For preparative cases, the acylgermanes were directly used in the ensuing condensation. Under UV light, all acylgermanes exhibit on TLC plates blue fluorescence, which facilitates identification.

General Procedure for the Preparation of Acylgermane *O*-Benzyl Oximes. To the respective triphenylacylgermane (2 mmol) in CH_2Cl_2 (12 mL) at 25 °C was added *O*-benzylhydroxylamine (0.5 g, 4 mmol, prepared from deprotonation of *O*-benzylhydroxylamine hydrochloride). After 5 min, a catalytic amount of concentrated HCl (aq) (1 drop) was added, and the reaction mixture was stirred overnight. The cloudy suspension was diluted with Et_2O (40 mL), extracted ($2 \times 5\%$ w/w citric acid (aq), $2 \times$ brine), and dried over Na_2SO_4 . Concentration in vacuo yielded the product, which was further purified by column chromatography.

General Procedure for the Preparation of *N,N*-Dimethylhydrazones. To a solution of the respective triphenylacylgermane (0.79 mmol) in CH_2Cl_2 (6 mL) at 25 °C was added *N,N*-dimethylhydrazine (0.30 mL, 3.95 mmol). After 5 min, a catalytic amount of concentrated HCl (aq) (1 drop) was added. After being stirred for 24 h, the cloudy suspension was diluted with diethyl ether and extracted ($2 \times 5\%$ w/w citric acid (aq), $2 \times \text{Et}_2\text{O}$, $2 \times$ brine), dried over MgSO_4 , and concentrated in vacuo. The crude product was further purified by column chromatography; in alternative experiments without HCl (aq) and simple concentration in vacuo, products were obtained in quantitative yield with comparable purity.

General Procedure for 5-Exo Cyclization Reactions.³¹ A solution of the radical precursor (for concentrations see Tables 3–5) in benzene- d_6 (400 μL) was prepared in an NMR

tube and degassed. A catalytic amount of AIBN and triphenyltin hydride (1.5–5.0 equiv) was added, and the reaction tube was immediately placed in a preheated oil bath (80 °C). After 90 min, the radical precursor was entirely consumed as shown by ^1H NMR analysis. The ratio between the cyclized and the reduced product was determined by integration of either the benzylic methylene singlets (*O*-benzyloxime ethers: reduced 5.05 ppm, cyclized 5.25 ppm) or the *N*-methyl singlets (*N,N*-dimethyl hydrazones: reduced 2.19 ppm, cyclized 2.55 ppm) in the ^1H NMR spectra taken in benzene- d_6 . All products showed spectral properties identical to those of authentic samples.

Photolytic Radical Initiation for Phenylseleno Radical Precursors via Acylgermanes or Hexamethylditin. To a degassed solution of **9e** (41.8 mg, 64.4 μmol) in benzene- d_6 (400 μL) in a quartz NMR tube was added acylgermane **8f** (3 mg, 7 μmol) or Me_6Sn_2 (2.2 mg, 7 μmol). The control experiment did not contain any initiator. Irradiation was carried out with a mercury lamp (254 nm) at 25 °C for 2 h (control experiment 10 h), and product identities and ratios were determined by NMR spectroscopy. The control showed only minor amounts of a terminal alkene (~8%) along with unchanged starting material. With radical initiator, conversion to the cyclized product **15** and a small amount of unreacted starting material (13.5% (with **8f**), 5.3% (with Me_6Sn_2)) occurred.

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Supporting Information Available: Full experimental data and characterization of prepared acids, acid chlorides, acylgermanes, acylgermane oxime ethers, acylgermane hydrazones, and authentic cyclization products. ^1H NMR spectra for **7e,g**, **8d–g**, **9a–g**, **10e,f**, **11**, **16**, **17E**, **17Z**, **21**, **24**, and **25** and ^{13}C NMR and DEPT-spectra for **17E**, **17Z**. Assignment of configurational isomers for **9a,c** (41 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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(31) The rate constant for cyclization is calculated as: $k_c = [\text{Cycl}]/[\text{Red}] \cdot [\text{HSnPh}_3]_{\text{eff}} \cdot k_1$. The Ph_3SnH is consumed during the reaction; thus, the "effective tin hydride concentration" $[\text{HSnPh}_3]_{\text{eff}}$ was calculated as the concentration of HSnPh_3 at 50% conversion of the radical precursor. This value for $[\text{HSnPh}_3]_{\text{eff}}$ is a close approximation to the result employing the integration equation. To estimate the rate constant for reactions of primary radicals with Ph_3SnH , we multiplied the rate constant for reactions of primary radicals with Bu_3SnH (ref a) times 4 (refs b, c): $k_1 = 2.5 \times 10^7 \text{ M}^{-1} \text{ s}^{-1}$ at 80 °C. (a) Chatgililoglu, C.; Ingold, K. U.; Scaiano, J. C. *J. Am. Chem. Soc.* **1981**, *103*, 7739. (b) Walling, C.; Cioffari, A. *J. Am. Chem. Soc.* **1972**, *94*, 6059–64. (c) Carlsson, D. J.; Ingold, K. U. *J. Am. Chem. Soc.* **1968**, *90*, 7047–55.