coupling reaction is also critical. Using our optimized coupling conditions,[19] peptide **4** was coupled to **3** to afford the glycopeptide **6** in good yield (entry 1). However, using the O-acetylated nucleophile **2**,[23] no significant coupling was observed (entry 2). This result, which is consistent with our earlier experience[14] and the low yields obtained in the past using **2** as the amine component,[11] may be due to the decreased nucleophilicity of **2** relative to **3**.[25]

In contrast to peptide **4**, peptide **7** should be optimally disposed for cyclization;[13] however, using our conditions,[19] a 53% yield of glycopeptide **9** was isolated with minimal succinimide formation (entry 7). Glycosylamine **3** has also been coupled to peptides **10** and **12**[26] to provide the glycopeptides **11** (58% purified yield) and **14** (61%), respectively (entries 6 and 8).[15,19] Our current focus is to test the limits of this reaction regarding the size of each component and to adapt this coupling procedure to a solid-phase methodology which allows for selective deprotection of a single carboxyl group at the desired aspartic acid. This procedure[19] has been used to successfully glycosylate resin-bound aspartic acid.[27] Preliminary ^{1}H NMR experiments of glycopeptides **6** and **11** indicate that the attached carbohydrate may influence the conformation of the peptide chain, possibly via the formation of a hydrogen bond.[28] The availability of a wide variety of synthetic glycopeptides will enable us to elucidate these important interactions.

Acknowledgment. We thank Beth Berger for synthesizing and purifying H_2N-WDAS-$CONH_2$[14] and Dr. Chris Warren for his helpful advice. We are grateful to Dr. Ioannis Papyannopoulos of the MIT MS facility (NIH Grant no. RR00317) for FABMS analyses. This work was supported by a grant from the Office of Naval Research (Molecular Recognition Program), the donors of the Petroleum Research Fund, administered by the American Chemical Society, and funds from the Camille and Henry Dreyfus Foundation (New Faculty Award) and Merck & Co. (Faculty Development Award).

(23) A method for the conversion of peracetylated oligosaccharides with GlcNAc at the reducing terminus to the β-glycosylamine and subsequent coupling to an amino-protected aspartic acid ester has been reported.[7] We have modified that procedure to minimize handling of the unstable glycosyl amine as follows: the β-glycosylazide[7b,8] was treated with 1,3-propanedithiol[24] (5 equiv) and diisopropylethylamine (3 equiv) in dimethylformamide (DMF) for 1.5 h at 23 °C to afford the β-glycosylamine **2**. Solvent was removed in vacuo, and the crude product was coupled directly.[12]

(24) Bayley, H.; Standring, D. N.; Knowles, J. R. *Tetrahedron Lett.* **1978**, 3633.

(25) A referee suggests that the observed difference in yield may simply be due to the lability of **2** under the reaction conditions. Although the rearrangement (see ref 7b) and dimerization (Paul, B.; Korytnyk, W. *Carbohydr. Res.* **1978**, *67*, 457) of **2** are precedented, we feel that this explanation is unlikely in light of the successful coupling of **2** to Boc-Asp(α-Bn) (see ref 12).

(26) Peptide **12** is derived from the glycosylation site of ovalbumin. Glabe, C. G.; Hanover, J. A.; Lennarz, W. J. *J. Biol. Chem.* **1980**, *255*, 9236.

(27) Fluorenylmethoxycarbonyl (Fmoc) protected aspartic acid bound to the polystyrene-based methylphenacyl resin[29] was treated with **3** (2 equiv), HBTU (3 equiv), and HOBt (1 equiv) in DMF/DMSO. After shaking for 25 h, the resin was photolyzed (350 nm, DMF/2 equiv of H_2O, 23 h, 23 °C) to provide the product Fmoc-Asn(GlcNAc), as well as some unreacted Fmoc-Asp (~4:1 glycoamino acid to starting material, by HPLC).

(28) Glycopeptides **11** and **6** were analyzed (^{1}H NMR, 300 MHz, DMSO) over the temperature range 20–50 °C. For **11**, the chemical shifts of two amide protons were relatively insensitive to temperature ($\Delta\delta/\Delta T \leq 3.5$ ppb/deg), indicating the participation of these protons in hydrogen bonds.[11] For **6**, one amide proton appears to be involved in hydrogen bonding. Details of these and other NMR experiments will be published elsewhere.

(29) Wang, S. S. *J. Org. Chem.* **1976**, *41*, 3258.

Photochemical Intramolecular Cyclization Reactions of Acylgermanes[1]

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Summary: The first photochemical intramolecular cyclization reaction of acyltriphenylgermanes to give 5- and 6-membered cyclic ketones bearing α-(triphenylgermyl)-methyl group is described.

There has been rapid development of a large number of remarkable organic reactions with functionalized silicon reagents. In contrast, development of germanium chemistry has been quite restricted. The utilization of organogermanium compounds in organic synthesis has, however, begun to generate considerable interest.[2] For example, acylgermanes under UV irradiation have recently been shown to mainly undergo a Norrish type-I reaction to generate a germyl and acyl radical pair, via the acylgermyl S_1 state.[3] On the other hand, photochemical reactions of acylsilanes,[4-6] lead to a nucleophilic siloxycarbene formed from the acylsilane T_1 state, which undergoes intermolecular reaction with a variety of reagents and/or proceeds to a Norrish type-II reaction involving γ-H abstraction and fragmentation. Consequently, the photochemical reactions characteristic of acylgermanes can be of interest as a novel means of generating acyl radicals.[7] The purpose of this paper is to demonstrate that acylgermanes are useful photoprecursors to acyl radicals and

(1) Presented in part at the 1989 International Chemical Congress of Pacific Basin Societies, Honolulu, December 17–22, 1989 (Abstracts of Papers, ORGN 439).

(2) (a) Oda, H.; Morizawa, Y.; Oshima, K.; Nozaki, H. *Tetrahedron Lett.* **1984**, *25*, 3217. Oda, H.; Oshima, K.; Nozaki, H. *Chem. Lett.* **1985**, 53. (b) Yamamoto, Y.; Hatsuya, S.; Yamada, J.-I. *J. Org. Chem.* **1990**, *55*, 3118. (c) Inoue, S.; Sato, Y. *Organometallics* **1987**, *6*, 2568. Inoue, S.; Sato, Y.; Suzuki, T. *Ibid.* **1988**, *7*, 739. (d) Kitching, W.; Olszowy, H. A.; Harvey, K. *J. Org. Chem.* **1982**, *47*, 1893. Wickham, G.; Young, D.; Kitching, W. *Organometallics* **1988**, *7*, 1187. (e) Sano, H.; Miyazaki, Y.; Okawara, M.; Ueno, Y. *Synthesis* **1986**, 776. (f) Kauffnann, T.; Ilchmann, G.; Koenig, R.; Wensing, M. *Chem. Ber.* **1985**, *118*, 391. (g) Livantsova, L. I.; Perelygina, O. P.; Zaitseva, G. S.; Baukov, Yu. I. *Zh. Obshch. Khim.* **1984**, *54*, 1925. (h) Stanczyk, W. *J. Organomet. Chem.* **1986**, *299*, 15. (i) Soderquist, J. A.; Negron, A. *J. Org. Chem.* **1989**, *54*, 2462. (j) Chatani, N.; Horiuchi, N.; Hanafusa, T. *J. Org. Chem.* **1990**, *55*, 3393. (k) Kiyooka, S.; Nakata, M. *Chem. Lett.* **1988**, 721. Kiyooka, S.; Shiota, F.; Shibuya, T. *Ibid.* **1987**, 495. Kiyooka, S.; Miyauchi, A. *Ibid.* **1985**, 1829.

(3) (a) Mochida, K.; Ichikawa, K.; Okui, S.; Sakaguchi, Y.; Hayashi, H. *Chem. Lett.* **1985**, 1433. (b) Taraban, M. B.; Maryasova, V. I.; Leshina, T. V.; Rybin, L. I.; Gendin, D. V.; Vyazankin, N. S. *J. Organomet. Chem.* **1987**, *326*, 347.

(4) Review: Ricci, A.; Degl'Innocenti, A. *Synthesis* **1989**, 647.

(5) Bourque, R. A.; Davis, P. D.; Dalton, J. C. *J. Am. Chem. Soc.* **1981**, *103*, 697 and references cited therein. Dalton, J. C.; Bourque, R. A. *Ibid.* **1981**, *103*, 699.

(6) Scheller, M. E.; Frei, B. *Helv. Chim. Acta* **1984**, *67*, 1734. Scheller, M. E.; Iwasaki, G.; Frei, B. *Ibid.* **1986**, *69*, 1378.

(7) (a) Giese, B. *Radicals in Organic Synthesis*; Pergamon Press: New York, 1986. (b) Boger, D. L.; Mathvink, R. J. *J. Org. Chem.* **1988**, *53*, 3377 and references cited therein. (c) Ryu, I.; Kusano, K.; Ogawa, A.; Kambe, N.; Sonoda, N. *J. Am. Chem. Soc.* **1990**, *112*, 1295. (d) Coveney, D. J.; Patel, V. F.; Pattenden, G. *Tetrahedron Lett.* **1987**, *28*, 5949. Patel, V. F.; Pattenden, G. *Ibid.* **1988**, *29*, 707.

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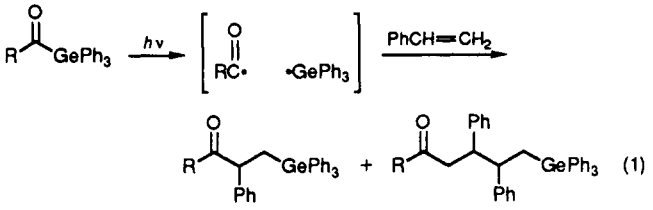
can be used in the synthesis of novel cyclic ketones bearing the α-(triphenylgermyl)methyl functional group.

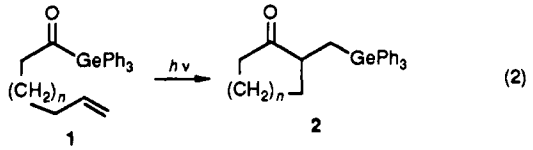
Acyltriphenylgermanes, readily available from the corresponding carboxylic acids,[8] have been reported to undergo a photochemically initiated intermolecular addition reactions in the presence of styrene to provide the formal $_{\sigma}2 + _{\pi}2$ and $_{\sigma}2 + _{\pi}2 + _{\pi}2$ adducts, in ca. 40% and 20% yields, respectively, as shown in eq 1.[9] The observation



(1)

that Ph_3Ge is found in both products suggests that the addition takes place before further diffusion of the germyl and acyl radical pair.

We imagined that a unique photochemical intramolecular cyclization reaction of acylgermanes 1 might provide ketones 2 regioselectively (eq 2).

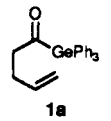
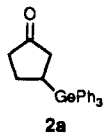
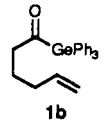
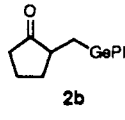
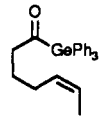
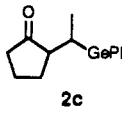
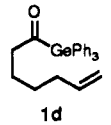
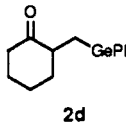
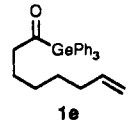
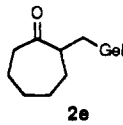
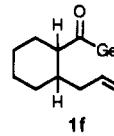
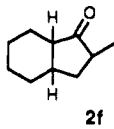
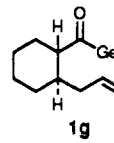
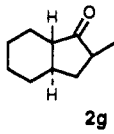
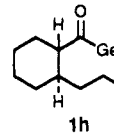
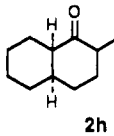
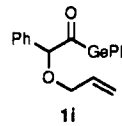
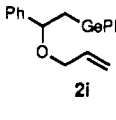
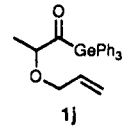
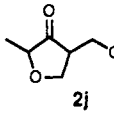
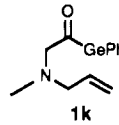
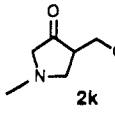
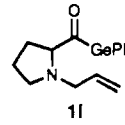
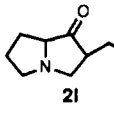


(2)

The results summarized in Table I show that the photochemical intramolecular cyclization reactions of acylgermanes proceed efficiently.[10] In most cases the products were isolated after silica gel chromatography in moderate to good yields along with some polymerized material.[11] It is suggested that the reactions presumably occur in solvent cages, so that only terminal olefins allow an effective approach of the bulky acyltriphenylgermyl moiety (entry 3). Cyclization to generate cyclopentanones proceeded smoothly (entries 2, 6, 7), and in the same manner, acylgermanes (**1i** and **1k**) having heteroatoms in the pendant chain afforded the corresponding 5-membered ketones (entries 10, 11). Cyclohexanones also were obtained in good yields (entries 4, 8). However, presumably for steric reasons, acylgermane **1c** having an internal olefin unit did not work,[12] and a process designed to provide a seven-membered cyclic ketone was strongly disfavored (entry 5). Furthermore, due to unfavorable steric factors which inhibit effective approach of the triphenylgermylcarbonyl and *N*-allyl groups, acylgermane **1e** did not undergo cyclization (entry 12).

In conclusion 5-*exo-trig* and 6-*exo-trig* modes of cyclization are apparently favored in these photochemical intramolecular cyclization reactions of acylgermanes **1**. The

Table I. Photochemical Intramolecular Cyclization Reactions of Acylgermanes

entry	acylgermane[a]	product[b]	% yield[c]
1	 **1a**	 **2a**	27
2	 **1b**	 **2b**	92
3	 **1c**	 **2c**	–[d]
4	 **1d**	 **2d**	86
5	 **1e**	 **2e**	–[d]
6	 **1f**	 **2f**	73
7	 **1g**	 **2g**	75
8	 **1h**	 **2h**	65
9	 **1i**	 **2i**	97
10	 **1j**	 **2j**	75
11	 **1k**	 **2k**	82
12	 **1l**	 **2l**	–[d]

[a] Acylgermanes were prepared in 40–70% yield from the corresponding ethyl esters, according to the previously reported method (ref 8). [b] All products exhibited the IR, ^1H NMR, and ^{13}C NMR spectra provided in the supplementary material, and satisfactory C, H, N elemental analyses. [c] Yields are based on products isolated by chromatography (SiO_2). [d] The expected products were not obtained (ref 10). [e] Trans:cis = 3:1, ratio determined by NMR.

(8) Kiyooka, S.; Shibuya, T.; Shiota, F.; Fujiyama, R. *Bull. Chem. Soc. Jpn.* **1989**, *62*, 1361.

(9) Kiyooka, S.; Hamada, M.; Matsue, H.; Fujiyama, R. *Chem. Lett.* **1989**, 1385.

(10) In a typical procedure, a solution of acylgermane 1 (0.01–0.02 M) in THF was irradiated with a 400-W high-pressure mercury lamp with stirring at ambient temperature under argon for 30 min. The reaction was monitored by TLC, and all cases required only 30 min to reach completion. After the solvent was removed with a rotary evaporator, the crude material obtained was purified by flash column chromatography to afford the corresponding cyclic ketone. When the intramolecular cyclization reaction did not proceed smoothly (entries 3, 5, 12), complex polymerized materials were obtained. Similar results were observed in the cyclization reaction with *n*-hexane instead of THF as a solvent.

(11) The case in entry 9, generating a stabilized benzylic radical, resulted in decarbonylation in preference to cyclization, as reported in ref. 8.

(12) All cyclization attempts with a variety of acylgermanes having an internal olefin unit were unsuccessful. For these acylgermanes the transition state is too sterically hindered to allow cyclization to occur.

chemistry offers a novel and effective method for the synthesis of 5- and 6-membered ring ketones. Continued exploration of the scope of the reaction and its applications are in progress. Some subsequential carbon–carbon bond formation reactions using the β-triphenylgermyl functionality produced in these reactions are being developed.

Acknowledgment. This research was supported by a Grant-in-Aid (No. 2640397) from the Ministry of Education, Science, and Culture of Japan. We thank Asami Germanium Research Institute for the generous gift of germanium tetrachloride.

Supplementary Material Available: Spectral data for products (**2a,b,d,f–k**) (4 pages). Ordering information is given on any current masthead page.

Allylic Transpositions of Enantiomerically Pure C1-Acyloxy (*E*)-Crotylsilanes: Stereospecific Synthesis of (*E*)-Vinylsilanes†

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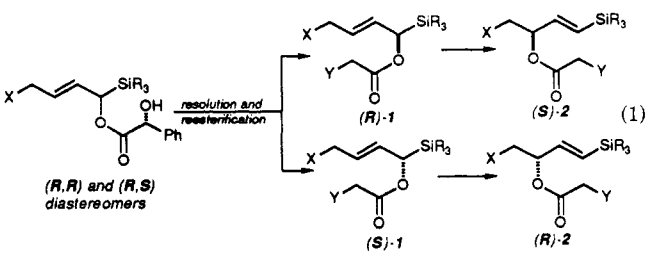
Summary: Treatment of (*R*)- or (*S*)-C1-acylated (*E*)-crotylsilanes **1** with catalytic amounts of boron trifluoride etherate or dichloropalladium bisacetonitrile [$PdCl_2(CH_3CN)_2$] in methylene chloride at room temperature resulted in an allylic transposition of the ester group with generation of optically active C3-oxygenated (*E*)-vinylsilanes.

The flexibility and skillful utilization of vinylsilanes in organic synthesis has rendered these molecules among the most versatile in modern organic chemistry.[2] Consequently, the development of new methodology which provides an expedient approach to the synthesis of this important class of organometallic compounds may have considerable potential. The inclusion of an oxygen functionality adjacent to the double bond and the ability to carry out the process in an asymmetric sense would further broaden its utility and scope. In addition to serving as precursors to carbonyl compounds[3] vinylsilanes function as effective vinyl anion equivalents that participate in a variety of carbon–carbon bond-forming processes including substitution[4] and cation π-cyclization reactions.[5] They have been employed in [4 + 2] cycloaddition strategies,[6] in Claisen rearrangements,[7] and more recently as precursors to alkylidene carbenes.[8] In conjunction with studies directed at the development of new methods for the asymmetric synthesis of biologically important hexoses from non-carbohydrate precursors we have had the opportunity to examine new methods for the preparation and utilization of homochiral C3-oxygenated (*E*)-vinylsilanes.[9] An attractive approach was the possibility of establishing a direct and stereospecific synthesis of an (*E*)-vinylsilane through a [3,3] sigmatropic rearrangement (*allylic transposition*) of an allylic silane system. The use of 1,2-disubstituted olefins adjacent to a geminally substituted (acyloxy)trialkylsilane center represented an intriguing possibility if an effective catalyst could be found to affect the desired rearrangement (eq 1). Herein we report our efforts to develop suitable reaction conditions that catalyze the suprafacial interchange of an ester functionality on homochiral C1-oxygenated (*E*)-crotylsilanes into optically active (*E*)-3-acyl-1-(trialkylsilyl)-1-butenoate derivatives.[10]



(1)

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(1) Recipient of a graduate fellowship from the Organic Chemistry Division of the American Chemical Society sponsored by Merck Sharp and Dohme, 1989–1990.

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(9) (a) The racemic 1-(trimethylsilyl)-2-buten-1-ol, precursor to (*S*)-**1a** and **1b**, was prepared from (*E*)-crotyl alcohol in 90% yield, via a reverse Brook rearrangement as reported by Danheiser: Danheiser, R. L.; Fink, D. M.; Okano, K.; Tsai, Y.-H.; Szczepanski, S. W. *Org. Synth.* **1987**, *66*, 14. Danheiser, R. L.; Fink, D. M.; Okano, K.; Tsai, Y.-H.; Szczepanski, S. W. *J. Org. Chem.* **1985**, *50*, 5393. The dimethylphenylsilyl derivatives, precursors to (*R*)-**1c–e** were prepared by the addition of lithium dimethylphenylsilane to crotonaldehyde to afford the desired racemic silane alcohols in good yield (70–80%) after purification on SiO_2 (see: Burke, S. D.; Saunders, J. O.; Oplinger, J. A.; Murtiashaw, C. W. *Tetrahedron Lett.* **1985**, *26*, 1131. Ager, D. J.; Fleming, I.; Patel, S. K. *J. Chem. Soc., Perkin Trans. 1* **1981**, 2520). Similarly, addition of (dimethylphenylsilyl)lithium to 4-(benzyloxy)-2-butenal gave the racemic alcohols that were used as precursors to (*R*)-**1f** and **1g**. The starting *E* aldehyde (Danishefsky, S. J.; Regan, J. *Tetrahedron Lett.* **1981**, *22*, 3919) was prepared by oxidation of the corresponding *Z* alcohol with PCC on silica gel (1:2 w/w) in CH_2Cl_2 (64% yield, see: Corey, E. J.; Suggs, J. W. *Tetrahedron Lett.* **1975**, *16*, 2647) or by Swern oxidation (99% yield, see: Swern, D.; Omura, K. *Tetrahedron* **1978**, *34*, 1651) to afford the 1-(dimethylphenylsilyl)-4-(benzyloxy)-2-buten-1-ol (**1d**) in 60% isolated yield. (b) The homochiral allyl silanes (*R*)- and (*S*)-**1** were obtained by resolution with (*R*)-*O*-acetylmandelic acid: Panek, J. S.; Sparks, M. A. *J. Org. Chem.*, submitted for publication. The absolute stereochemistry of the C1-hydroxy allylic silane precursors to (*R*)- and (*S*)-**1** was assigned from inspection of the ^1H NMR chemical shifts of the vinyl methyl and the silicon methyl groups of the derived (*R*)-*O*-acetyl mandelate esters by the method of Trost: Trost, B. M.; Belletire, J. L.; Godleski, S.; McDougal, P. G.; Balkovek, J. M.; Baldwin, J. J.; Christy, M. E.; Ponticello, G. S.; Varga, S.; Springer, J. P. *J. Org. Chem.* **1986**, *51*, 2370.

(10) All new compounds were isolated as chromatographically homogeneous materials and exhibited acceptable ^1H NMR, ^{13}C NMR, IR, and HRMS spectral data. All compounds were determined to be greater than 98% pure by ^1H NMR (400 MHz, 93.94 kG, operating at a S/N of 200:1).

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