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Radical Germylzincation of α -Heteroatom-Substituted Alkynes

Karen de la Vega-Hernández, Elise Romain, Anais Coffinet, Kajetan Bijouard, Geoffrey Gontard, Fabrice Chemla, Franck Ferreira, Olivier Jackowski, and Alejandro Perez-Luna*

Sorbonne Université, CNRS, Institut Parisien de Chimie Moléculaire, F-75005 Paris, France

ABSTRACT: The regio- and stereoselective addition of germanium and zinc across the C–C triple bond of nitrogen-, sulfur-, oxygen-, and phosphorous-substituted terminal and internal alkynes is achieved by reaction with a combination of R_3GeH and Et_2Zn . Diagnostic experiments support a radical-chain mechanism and the β -zincated vinylgermanes that show exceptional stability are characterized by NMR spectroscopy and X-ray crystallography. The unique feature of this new radical germylzincation reaction is that the $C(sp^2)$ –Zn bond formed remains available for subsequent *in situ* Cu(I)- or Pd(0)-mediated C–C or C–heteroatom bond formation with retention of the double bond geometry. These protocols offer a modular access to elaborated tri- and tetrasubstituted vinylgermanes decorated with heteroatom substituents β to germanium that are useful for the preparation of stereodefined alkenes.

INTRODUCTION

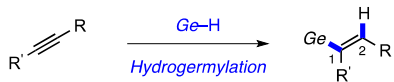
Vinylgermanes¹ are attractive synthetic building blocks that offer specific features such as increased stability towards protonolysis,² facile halodegermylation³ or low toxicity,⁴ which make them useful when limitations are met with the more popular group 14 homologues vinylsilanes and vinylstannanes.⁵ Hence, the preparation of vinylgermanes is a field of intense ongoing research. A number of approaches have proved suitable for the preparation of vinylgermanes,^{1c} including electrophilic substitution of vinylmetals with halogermanes,^{3b,6} Pd-catalyzed germylation of vinyl halides,⁷ hydro-^{3a,8} or carbometalation⁹ of alkynylgermanes, radical substitution of vinylsulfides,^{10a} -stannanes,^{10a} or -sulfones,^{10b} alkene germylation through coupling with hydrogermanes¹¹ or with vinylgermanes,¹² olefination of acylgermanes,¹³ or domino arylgermylation of oxanorbornadiene / retro-Diels-Alder.¹⁴ Yet, the direct synthesis of vinylgermanes from alkynes by carbon-germanium bond-forming addition reactions represents the most straightforward approach and has received the greatest attention. The hydrogermylation of alkynes with hydrogermanes has been disclosed through thermal or microwave-activated,¹⁵ radical,¹⁶ transition-metal-catalyzed,^{3a,8d,16e,17} as well as main-group Lewis-acid-catalyzed addition processes.¹⁸ These protocols offer high levels of regio- and stereocontrol, but a shared fundamental limitation is that they cannot provide access to derivatives having two substituents distal to the position of the alkene germyl group (Scheme 1, top). Furthermore, only some of the aforementioned synthetic alternatives have been implemented for this purpose,^{6,9,10,13b} and they rely on more elaborated starting materials and are not wide-in-scope. Thus, there is no direct and general solution available for the regio- and stereoselective preparation of 1,2,2-trisubstituted or tetrasubstituted vinylgermanes.

To satisfy this demand, alkyne germylmetalation, i.e. the 1,2-addition of germanium–metal bonds across the carbon–carbon triple bond of alkynes, is particularly appealing as it establish-

es in a single synthetic operation a $C(sp^2)$ –Ge bond and a $C(sp^2)$ –metal bond. The newly formed reactive bond can be used as linchpin for subsequent C–C bond formation in one pot following electrophilic substitution. However, in sharp contrast with the related silylmetalation and stannylmetalation reactions that are prevalent approaches for the preparation of polysubstituted vinylsilanes¹⁹ and vinylstannanes,²⁰ germylmetalation reactions are almost unknown. The reaction between (trimethylgermyl)copper and a terminal alkyne was reported to be low yielding.²¹ Also, the germylcupration of terminal acetylenes with (triethylgermyl)- and (triphenylgermyl)cuprates was disclosed:²² excellent *cis* stereoselectivity was observed, but regiocontrol was only achieved with the triphenylgermyl reagents. In that case however, the addition was found to be reversible and in favor of the starting materials; hence vinylgermane formation only proceeded in the presence of a proton donor and the $C(sp^2)$ –Cu bond formed was not available for subsequent elaboration.²³ It is also worthy of mention that protocols for the related alkyne germylstannation were developed using the oxidative addition chemistry of Ge–Sn compounds.^{24–26} Nonetheless, following this approach, subsequent elaboration of the $C(sp^2)$ –Sn bond required an additional synthetic step.²⁷

Scheme 1. Synthesis of Vinylgermanes from Alkynes with C–Ge bond formation (Ge = triorganogermyl)

Hydrogermylation of C–C triple bonds (previous work)



R = Aryl, alkyl, silyl, CO₂R; R' = H, aryl, alkyl, CF₃

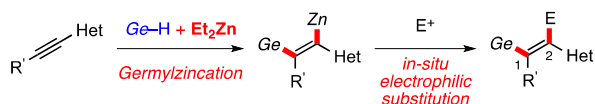


1,2-disubstituted

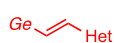


1,1,2-trisubstituted

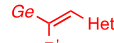
Germylzincation of C–C triple bonds (this work)



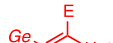
Het = [N], [S], [O], [P]; R' = H, aryl, alkyl, CF₃; E = [C], [S], I, Br, F, CF₃



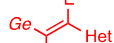
1,2-disubstituted



1,1,2-trisubstituted



1,2,2-trisubstituted



tetrasubstituted

Here we focus on α -heteroatom-substituted alkynes, a substrate class that has not been considered previously for the above-described methods and that would deliver valuable heteroatom-substituted alkenes.²⁸ We describe the regio- and stereoselective germylzincation of both terminal and internal nitrogen-, oxygen-, sulfur- and phosphorus-substituted alkynes by reaction with a combination of a hydrogermane and Et₂Zn (Scheme 1, bottom). Upon hydrolysis of the C(sp²)–Zn bond or *in situ* Cu(I)- or Pd(0)-mediated functionalization, this method gives access to a variety of original di-, tri- and tetrasubstituted vinylgermanes. As part of this work, we also demonstrate the synthetic potential of this construction of orthogonally 1,2-dimetalated alkenes.

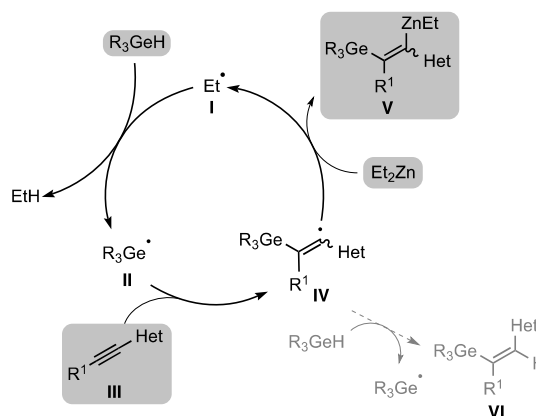
Our idea, shown in Scheme 2, was to develop a radical approach similar to the one we recently applied to obtain the silylzincation of terminal α -heteroatom-substituted alkynes using a combination of (Me₃Si)₃SiH and Et₂Zn.²⁹ We reasoned that germanium-centered radicals **II**, produced by H-atom transfer between hydrogermanes and ethyl radical (**I**→**II**), should add readily across the C–C triple bond of α -heteroatom-substituted alkynes **III** to provide regioselectively α -heteroatom-substituted vinylic radicals **IV** (**III**→**IV**). Radicals **IV** would then react with Et₂Zn by homolytic substitution (S_H2) at the zinc atom (**IV**→**V**) to afford β -zincated vinylgermanes **V** along with ethyl radical **I** that would propagate the radical chain. For such a process to be possible, radical **IV** would have to undergo Zn-atom transfer (**IV**→**V**) faster than competitive H-atom transfer from R₃GeH (**IV**→**VI**). Otherwise, radical hydrogermylation¹⁶ would be the main reaction outcome and the Zn functionality would be lost.

Estimation of the rate coefficients for each elementary step involved provided support for the feasibility of this radical chain, as they were all expected to be well above 10² M⁻¹ s⁻¹, the commonly accepted lower limit for a radical chain to propagate in dilute solutions.³⁰ Triaryl- and trialkylgermanes undergo H-atom abstraction from alkyl radicals with rate constants in the range of 10⁵–10⁶ M⁻¹ s⁻¹ at ca. 30 °C.³¹ Moreover, it is also important to emphasize here that the rate for the addition of the ethyl radical across alkynes with α -heteroatom substituents should be lower than ~10⁵ M⁻¹ s⁻¹, which is the rate for the addition of alkyl radicals across propiolates (terminal alkynes with a strong electron-withdrawing substituent):³²

thus, direct ethyl radical addition leading to carbozincation products should be avoided. The rate constant for the addition of germanium-centered radicals across alkynes has not been determined,³² but it should be of the same order of magnitude (though lower) than that for additions of silyl-centered radicals³³ (1 × 10⁸ M⁻¹ s⁻¹ at 27 °C for the addition of the triethylsilyl radical across phenylacetylene).³² While little is known about the rate for the reaction between vinyl radicals and Et₂Zn, our previous work on radical silylzincation demonstrates that for α -heteroatom-substituted vinylic radicals (**IV**), the rate for S_H2 at the zinc atom is suitable for chain propagation and can outcompete H-atom transfer from (Me₃Si)₃SiH.²⁹ Given that the rates for radical H-abstraction are in comparable ranges for R₃GeH and for (Me₃Si)₃SiH,³¹ a similar situation was expected here.

Finally, regarding the initiation of the radical chain (not shown in the scheme), we surmised that it could occur, even in the absence of deliberately added radical initiators, through several pathways, including spontaneous^{17b,34} or light³⁵-induced homolysis of the Ge–H bond (as for the hydrogermylation reactions)³⁶ or oxidation of diethylzinc by traces of molecular oxygen.^{37, 38}

Scheme 2. Anticipated Radical Approach to the Germylzincation of α -Heteroatom-Substituted Alkynes

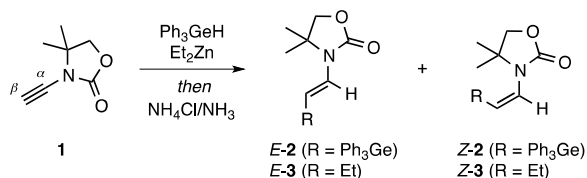


RESULTS AND DISCUSSION

We commenced our study by investigating the germylzincation of model terminal ynamide **1** with Ph₃GeH, a well-established radical hydrogermylating reagent that is commercially available and easy-to-handle (Table 1). The initial conditions involving 1.3 equiv of hydrogermane and 3.0 equiv of Et₂Zn at 0 °C in *n*-hexane, led to the exclusive formation of β -germylenamide **2** as an *E/Z* = 30:70 mixture of isomers, but the reaction was not complete and only ~ 60% of **1** was consumed (Entry 1). In fact, competitive deprotonation of **1** by Et₂Zn as well as direct hydrogermylation delivering *Z*-**2** hampered the germylzincation process. A survey of other solvents was then carried out. While no significant improvement was observed in CH₂Cl₂ and Et₂O, reactions in benzene and methyl *tert*-butyl ether (MTBE) afforded improved conversion (~ 80%). The stereoselectivity was only modest but, by contrast with the reaction in *n*-hexane, often in favor of the *E* isomer. Furthermore, in MTBE, competitive carbozincation giving **3** was also observed. Eventually, full conversion and total stereocontrol, also in favor of the *E* isomer, were obtained using Me-THF and THF. Nevertheless, carbozincation of **1** occurred to some extent with the more hindered ether, and

a better yield in **2** (87% vs 64%) was obtained in THF. With lower amounts of Et₂Zn (1.8 or 1.2 equiv), the reaction also took place with high conversion and exclusive formation of **2**, albeit with lower stereocontrol.

Table 1. Optimization of the Germylzincation of Ynamide **1**

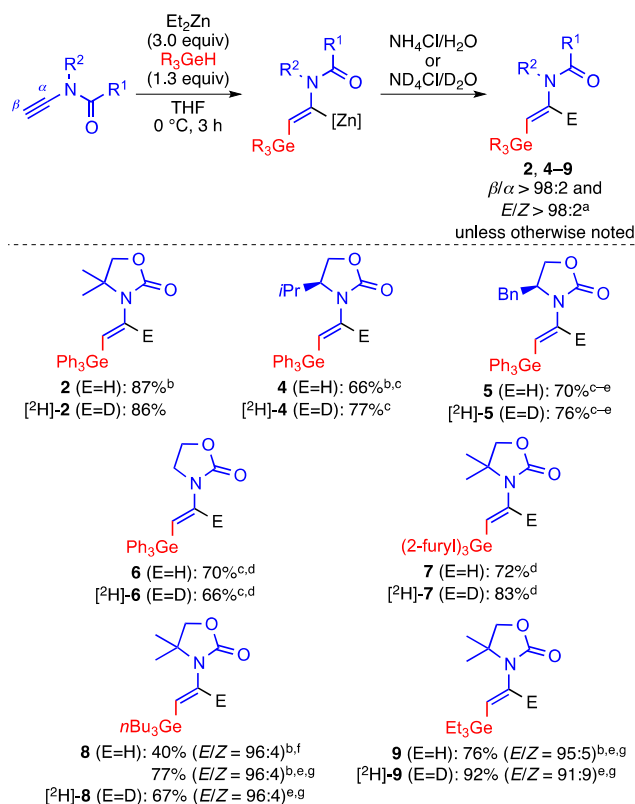


Entry	Solvent ^a	Et ₂ Zn [equiv]	Conversion ^{b,c} (2/1)	d.r. 2 (E/Z) ^c	Yield 2 (%) ^d
1	<i>n</i> -hexane ^c	3.0	62:38	30:70	nc ^f
2	CH ₂ Cl ₂	3.0	50:50	70:30	37
3	Et ₂ O	3.0	54:46	48:52	29
4	benzene	3.0	85:15	57:43	nc ^f
5	MTBE	3.0	80:20	68:32	62 ^g
6	Me-THF	3.0	>99:1	98:2	64 ^h
7	THF	3.0	>99:1	>98:2	87
8	THF	1.8	>99:1	90:10	nc ^f
9	THF	1.2	89:11	76:24	nc ^f

^aReaction conditions: Ph₃GeH (1.3 equiv), 0 °C, 3 h unless otherwise stated. ^bOnly β-germylated regioisomers were detected. ^cDetermined by ¹H NMR prior to purification. ^dCombined yield of isolated diastereomers. ^eReaction time = 6 h. ^fNot calculated. ^g6% of **3** was observed. ^h10% of **3** was observed.

The scope of this new germylzincation reaction of terminal ynamides was next considered (Scheme 3). Modification of the substitution pattern α to the nitrogen atom of the oxazolidinone ring was well tolerated and β-germylenamides **4–6** were isolated in good yields and as single *E* isomers.³⁹ Here however, small amounts (10–12%) of carbozincation adducts were detected in the crude. Other hydrogermanes were also used. Trifurylgermane⁴⁰ reacted smoothly to provide stereopure *E*-**7** in 72% yield. With *n*Bu₃GeH, the conversion (50%) was not complete and product **8** was obtained in a lower 40% yield along with 10% of the carbozincation adduct (**3**). In this case, the rate coefficient for the reaction between alkyl radicals and the hydrogermane is around one order of magnitude lower than for triarylgermanes;⁴¹ this makes ethyl radical addition more competitive and the propagation of the radical chain (Scheme 2, **I**→**II**) less efficient. Nevertheless, with higher amounts of hydrogermane (2.0 equiv) and longer reaction times, *n*Bu₃GeH and Et₃GeH led respectively to **8** and **9** in high yields with very high (≥ 95:5) stereoselectivities, and no ethylzincation was observed.

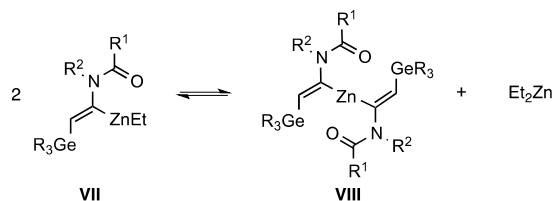
Scheme 3. Reaction Scope for the Germylzincation of Terminal Ynamides



^aMeasured by ¹H NMR prior to purification. ^bReaction was quenched with NH₄Cl/NH₃. ^c10–12% of Et addition was detected. ^dCuTC (1.0 equiv) was added before the reaction quench. ^e16 h reaction time. ^f10% of **3** was formed. ^gR₃GeH (2.0 equiv).

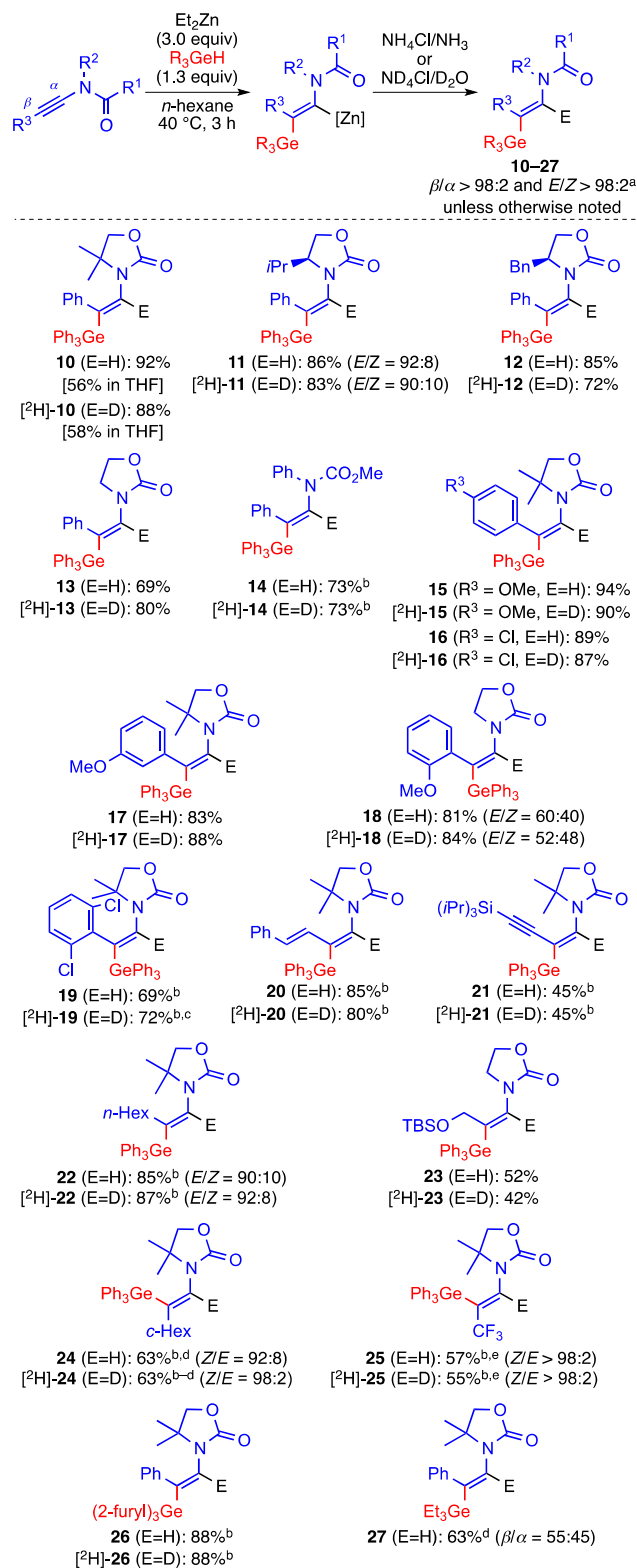
The formation of vinylzinc intermediates upon reaction with R₃GeH / Et₂Zn under the developed conditions was studied systematically by deuterium labeling and D-incorporation > 95% at the α-position was observed in every case (Scheme 3). It must be noted however that these experiments were complicated by the remarkably high stability towards hydrolysis of the C(sp²)–Zn bond of divinylzinc species **VIII** (Scheme 4), likely formed by Schlenk equilibration of the intermediates **VII** arising from germylzincation (*vide infra*). In some cases, organometallic species **VIII** reacted only partially with ND₄Cl/D₂O⁴² or MeOD, leading to flawed D-incorporation values and significant amounts of **VIII** were recovered in the crude even after extended exposure to aqueous solutions or after column chromatography on silica gel! Efficient deuterio-demetalation of intermediates **VIII** was nevertheless achieved upon addition of CuTC (Copper(I)-thiophene-2-carboxylate) prior to the reaction quench and reliable D-labeling data could be collected. Similar quench conditions (CuTC / NH₄Cl / H₂O) were also used in the preparation of non-labeled **5**, **6** and **7**.

Scheme 4. Schlenk Equilibrium of α-Zincated β-Germylenamides



Importantly, the germylzincation reaction was also found to be well suited for internal yniamides (Scheme 5).

Scheme 5. Reaction Scope for the Germylzincation of Internal Yniamides



^aMeasured by ^1H NMR prior to purification. ^b16 h reaction time. ^cCuTC (1.0 equiv) was added before the reaction quench. ^d2.0 equiv R_3GeH . ^e13% of Et addition and 9% of an α -isomer were detected.

For this substrate class, the best conditions for the reaction with Ph_3GeH / Et_2Zn involved using n -hexane as solvent at $40\text{ }^\circ\text{C}$. Here, direct hydrogermylation did not interfere with the germylzincation process, and β -germylenamide **E-10** was obtained from the parent Ph-substituted yniamide in 92% yield with β -regioselectivity and *cis*-stereoselectivity. The same exquisite regio- and stereoselectivity was observed at lower temperatures and/or in THF, but conversion of the starting material was not complete.

Modification of the nitrogen substituent was also well tolerated here. *E*-enamides **11–13** having different oxazolidinone rings were obtained in 69–86% yields from the corresponding cyclic yniamides. Importantly and by contrast with the terminal yniamides derived from the same oxazolidinones, competing ethyl radical addition was not observed, what is consistent with the lower rate coefficient for the addition of alkyl radicals to disubstituted alkynes than to monosubstituted alkynes.³² Moreover, enamide **14** having an acyclic carbamate was produced, with full regio- and stereoselectivity, in 73% yield. The *E* configuration of products **12** and **14** was established by X-ray crystallographic analysis.⁴³

Regardless of the electronic character or the position of the substituent, substitution of the phenyl ring had little impact on the reaction outcome with other aryl-substituted yniamides. Thus, **15** and **17** with *para*- or *meta*-methoxy-substituted rings, or **16** and **19** with *para* chloro- or *ortho*, *ortho* dichloro-substituted rings were all obtained in similar high yields and as single *E* isomers. Only **18** having an *ortho* methoxy-substituted phenyl ring was an exception to this trend as it was delivered with low stereoselectivity. Certainly, coordination of Et_2Zn to the MeO group influences the alkylzinc group transfer event that is the stereodiscriminating step (*vide infra*).

The germylzincation was not restricted to yniamides substituted at the alkyne terminus by aryl groups, as trisubstituted enamides having alkenyl (**20**-), alkynyl (**21**-), primary alkyl (**22** and **23**-), secondary alkyl (**24**-), and CF_3 (**25**-) substituents β to the nitrogen atom were prepared for the most part in good yields, even if longer reaction times were sometimes necessary. Excellent stereoselectivities were obtained in all cases, but for cyclohexyl- and CF_3 -substituted enamides **24** and **25**, reversal of stereoselectivity in favor of a *trans*-selective germylzincation was observed. Furthermore, in the formation of the CF_3 -substituted enamide, competitive carbozincation and α -selective germylzincation were detected to some extent. The configurations of products **23** (*E*) and **25** (*Z*) were established by X-ray crystallographic analysis.⁴³

As demonstrated with the preparation of **26** as a single *E* isomer in 88% yield, $(2\text{-furyl})_3\text{GeH}$ performed as well as Ph_3GeH for the germylzincation of internal yniamides. By contrast, trialkylgermanes were not suitable because of the lack of regiocontrol, as in the case of the formation of **27**.

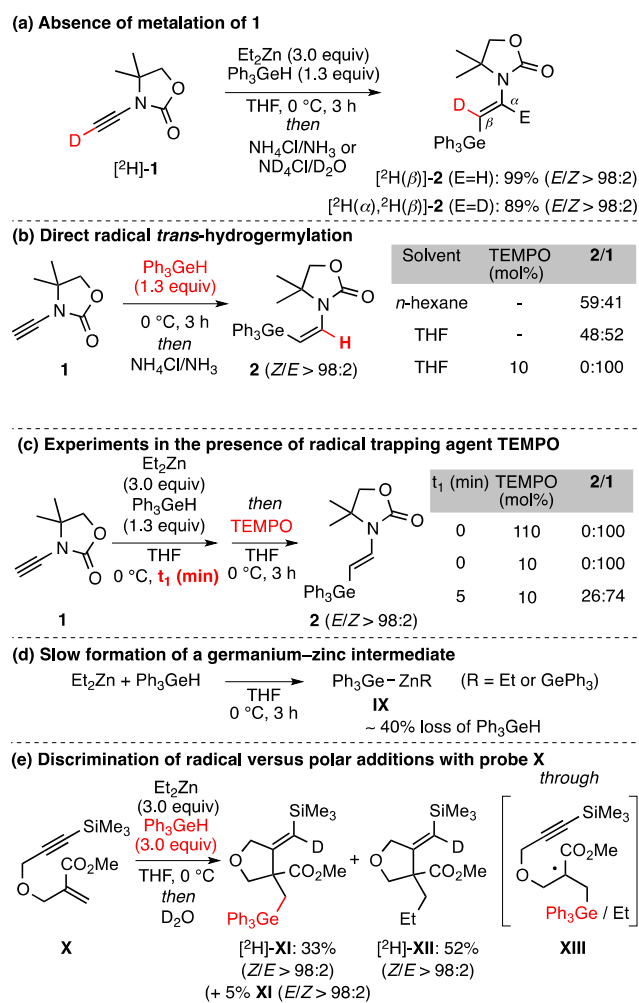
Finally, similarly to the reactions involving terminal yniamides, D-labeled enamides (> 90% D-incorporation) were obtained on quenching the reactions with ND_4Cl (Scheme 5), thus confirming the formation of vinylzinc intermediates upon reaction of internal yniamides with R_3GeH / Et_2Zn . Again, in the cases of **19** and **24**, quenching with a mixture of CuTC / ND_4Cl / D_2O was necessary to obtain reliable values for D-incorporation.

Our next efforts were directed to gain insight into the mechanism of the new germylzincation reaction. In a first set of

experiments, we examined the influence of metalation of **1** in the reaction media (Scheme 6, a). Performing the gerymzincation on D-labeled ynamide [²H]-**1** led exclusively to *E*-[²H(β)]-**2** without loss of deuterium at the β -position, thus indicating that deprotonation of **1** (neither by Et₂Zn⁴⁴ nor by vinylzinc intermediates) did not occur during gerymzincation (in THF at 0 °C).

It was found that Ph₃GeH could react with **1** in the absence of Et₂Zn (Scheme 6, b):⁴⁵ both in *n*-hexane and THF, after 3 h at 0 °C, the stereoselective formation of *Z*-**2** was observed in 50–60% yield,⁴⁶ and the absence of this direct hydrogermylation in the presence of TEMPO confirmed its radical character.⁴⁷ The afore-described D-labeling experiments (Scheme 3) established that gerymzincation outcompetes this radical hydrogermylation in THF with excess Et₂Zn. However, the loss of stereoselectivity observed with lower amounts of Et₂Zn or in other solvents (Table 1), can certainly be ascribed to the coexistence of the two competing processes: gerymzincation that leads to the *E*-isomer (after work-up), and hydrogermylation that delivers the *Z*-isomer. It is important to note that, by contrast, with internal ynamides, no reaction with Ph₃GeH was detected in the absence of Et₂Zn, even at 40 °C.

Scheme 6. Mechanistic Studies



The presence of TEMPO also thwarted completely the gerymzincation (Scheme 6, c): no conversion was observed if amounts as low as 10 mol% were added at the beginning and only 26% of *E*-**2** was formed upon addition after 5 min of

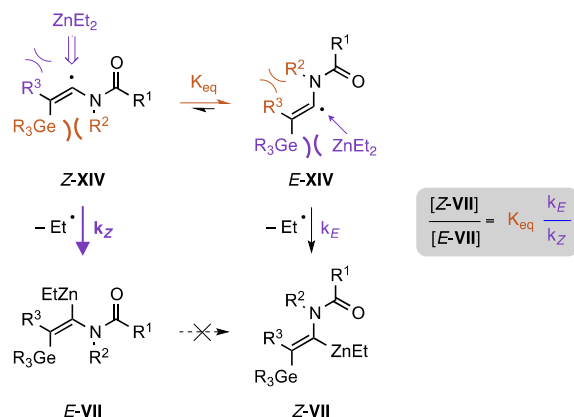
reaction. While these experiments lend clear evidence for the intervention of radicals in the mechanism, we could not at this point exclude a scenario wherein Et₂Zn would react with R₃GeH by a radical alkylzinc group-transfer process (reminiscent of that involved in the formation of [(Me₃Si)₃Si]₂Zn from (Me₃Si)₃SiH and Et₂Zn⁴⁸ and provide a putative germanium–zinc intermediate **IX** (Scheme 6, d) that would add across the C–C triple bond of the ynamide through a polar mechanism. Notably, the reported formation of (Ph₃Ge)₂Zn by reaction between Et₂Zn and Ph₃GeH in THF required to exclude this possibility.⁴⁹ Towards this end, the reaction of Ph₃GeH / Et₂Zn with mechanistic probe **X**^{29a} was considered (Scheme 6, e). The formation of cyclized products [²H]-**XI** (33%) and [²H]-**XII** (52%) (arising from competing ethyl radical addition)⁵⁰ provided evidence for a radical 1,4-addition (leading to an intermediate β -alkoxy radical **XIII** that undergoes 5-*exo*-dig ring closure) whereas no products arising from the fragmentation of an intermediate β -alkoxy anion⁵¹ (not shown) that would support an alternative polar addition of **IX** were detected. Furthermore, we also monitored by *in situ* ¹H NMR the rate of depletion of Ph₃GeH upon contact with Et₂Zn in THF in the absence of ynamide. After 3 h at 0 °C (Scheme 6, d), 40% of the initial amount of Ph₃GeH had disappeared.⁵² Hence, the rate of formation of a hypothetical germanium–zinc intermediate under these conditions was too slow to account conveniently for the gerymzincation reactions. Overall, these findings provided strong support for the mechanism foreseen at the outset of our work (depicted in Scheme 2) involving the addition of germanium-centered radicals across the C–C triple bond of ynamides.

The regioselectivity of the process was fully consistent with this mechanism, as previous intermolecular additions of radicals across ynamides, including the abovementioned direct hydrogermylation, occurred β to the nitrogen atom both for terminal and internal ynamides.⁵³ Steric effects usually account for the regioselectivity of radical additions across monosubstituted alkynes,³² and this is likely also the case for terminal ynamides. By contrast, the origin of regioselectivity for internal ynamides is not clear. Steric factors still seem important, as shown by the lack of stereocontrol with the less hindered trialkylgermanes (Scheme 5, product **27**), but other elements, among which stabilization of the vinyl radical by the α -nitrogen atom, or differences in reactivity of the possible regioisomeric radicals in the subsequent forward reaction (S_H2 at zinc), can also intervene and are difficult to estimate.³²

The stereochemical outcome of the gerymzincation reactions was also rationalized conveniently on the basis of this scenario: the stereoselectivity of the gerymzincation reaction is that of the alkylzinc group transfer (i.e. **XIV**→**VII**, Scheme 7). sp²-Hybridized radicals **XIV** have a bent geometry and are considered to exist in two equilibrating diastereomeric forms with a low interconversion energy barrier. The reaction of *E*-**XIV** with Et₂Zn provides *Z*-**VII** and that of *Z*-**XIV** produces *E*-**VII**.⁵⁴ Thus, the *Z/E* ratio for the formation of **VII** depends both on the relative stability of both isomers of **XIV** (K_{eq}), as well as the relative ease of each diastereomeric form to undergo ethylzinc group transfer (k_Z vs k_E). In general terms, one would expect *Z*-**XIV** to react more promptly than *E*-**XIV** (k_Z > k_E) because the Et₂Zn/R³ steric interaction is less demanding than the Et₂Zn/R₃Ge interaction. With “small” R³ substituents (i.e. R³ = H, primary alkyl or aryl), the *Z/E* equilibrium is largely in favor of the *E* form (K_{eq} ≫ 1) and the formation of

Z-VII is favored. By contrast “larger” R^3 substituents (i.e. cyclohexyl or CF_3), destabilize **E-XIV** (K_{eq} becomes lower) and thus the formation of **E-VII** becomes more favorable.

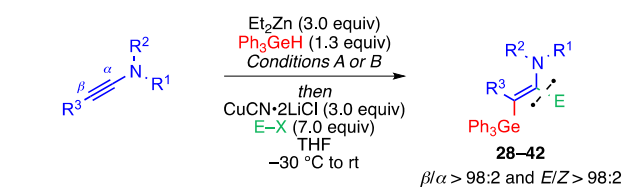
Scheme 7. Stereoselectivity Model for the Germylzincation of Terminal and Internal Ynamides



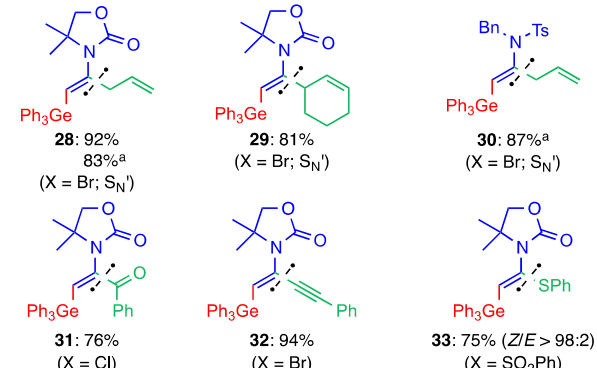
The reversal of stereoselectivity observed between the radical *trans*-silylzincation of terminal ynamides with $(Me_3Si)_3SiH$ / Et_2Zn in *n*-hexane^{29a} and the present *cis*-stereoselective germylzincation in THF is a noteworthy point that deserves further comment. The *trans* selectivity for the silylzincation was attributed to the formation, in *n*-hexane, of a Lewis pair between Et_2Zn and the carbonyl group on the nitrogen atom; the Zn-atom transfer step was accelerated and outcompeted Z-to-*E* interconversion of the α -amino vinylic radical that reacted only as the initially formed *Z*-stereomer.⁵⁶ As evidenced with *in situ* IR experiments, THF prevents this Lewis-pair formation during germylzincation (*see supporting information*). Hence, Z-to-*E* interconversion becomes faster than the Zn-atom transfer step; the reaction of the *E*-stereomer (i.e. **E-XIV** ($R^3=H$)) is favored and the formation of **Z-VII** ($R^3=H$) is obtained. The fact that silylzincation of terminal ynamide **1** with $(Me_3Si)_3SiH$ / Et_2Zn proceeds with exclusive *cis*-stereoselectivity in THF,⁵⁷ provides additional evidence for this remarkable solvent effect.

Having established the scope for the germylzincation reaction, we next investigated the synthetic potential of $C(sp^2)$ -Zn bond functionalization to provide access to vinylgermanes with two substituents β to the germanium atom. *In situ* Cu(I)-mediated electrophilic substitution following germylzincation occurred readily with complete stereoretention of the double bond geometry (Scheme 8). The typical procedure involved using the THF-soluble salt $CuCN \cdot 2LiCl$, but (commercially available) $CuTC$ could be used alternatively with comparable results. Both protocols were equally efficient for the vinylzinc intermediates arising from the germylzincation of terminal or internal ynamides, thus giving access to diversely substituted tri- or tetrasubstituted vinylgermanes with defined geometry. Competent carbon and non-carbon electrophiles included allylic halides (**28–30** and **34–38**), acyl halides (**31**), alkynyl bromides (**32, 40–42**), methyl iodide (**39**) or phenyl phenylthio sulfone (**33**). The *E* configuration of product **40** was established by X-ray crystallographic analysis.⁴³

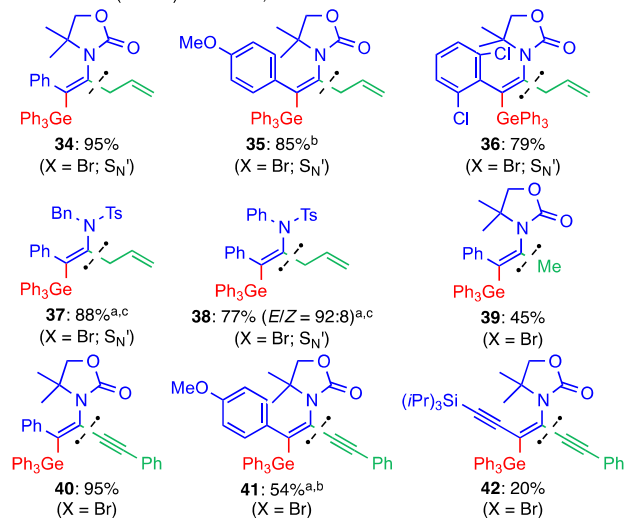
Scheme 8. Domino Ynamide Germylzincation / Cu(I)-Mediated Electrophilic Substitution



Conditions A ($R^3 = H$): THF, 0 °C



Conditions B ($R^3 \neq H$): *n*-hexane, 40 °C

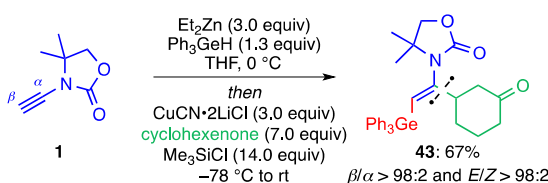


^a $CuTC$ was used as $Cu(I)$ -salt. ^bReaction performed at 1.0 mmol scale. ^cThe germylzincation was carried out with 2.0 equiv Ph_3GeH at rt.

Importantly, the domino *cis*-germylzincation–Cu(I)-mediated electrophilic substitution was also applicable with tosyl-ynamides (terminal and internal) and delivered α -substituted β -germyl enamides **30, 37** and **38** in 77–88% yield. It must be noted that the corresponding β -germyl enamides arising from protonolysis ($E = H$) decomposed during work-up and could not be isolated.

Moreover, *in situ* functionalization of the $C(sp^2)$ -Zn bond of the germylzincation adducts was also readily achieved by means of Cu(I)-mediated 1,4-addition to enones, as illustrated with the formation of adduct **43** from **1** (Scheme 9).

Scheme 9. Domino Ynamide Germylzincation / Cu(I)-Mediated 1,4-Addition



The presence of excess Et_2Zn required for the gerylzincation step complicated in certain cases clean $\text{C}(\text{sp}^2)\text{-Zn}$ bond functionalization, notably for halodezincation reactions. To overcome this limitation we decided to eliminate Et_2Zn before the electrophilic substitution step by removing the volatiles under reduced pressure. Upon elimination of Et_2Zn , displacement of the Schlenk equilibria (Scheme 4) led to the exclusive formation of divinylzinc intermediates.

In particular, the structure of compounds **44** and **45** was analyzed by X-ray crystallography and both showed similar characteristics (Figure 1). The *cis* geometry between zinc and germanium following gerylzincation was confirmed. An almost linear arrangement of the two carbon–zinc bonds was observed, with bond lengths (1.985 to 2.009 Å) in the expected range for diorganozinc compounds.⁵⁸ Remarkably, the zinc atom was also coordinated to the oxygen atoms of the carbonyl groups and adopted an uncommon distorted seesaw shaped four-coordinate geometry.⁵⁹ The position of the phenyl rings of Ph_3Ge is also of interest. Even though there is no $\text{Zn}\text{-C}_{\text{ipso}}$ contact, two of them clearly shield the Zn atom and likely confer to the divinylzinc species their unusual stability towards hydrolysis and oxidation mentioned previously.

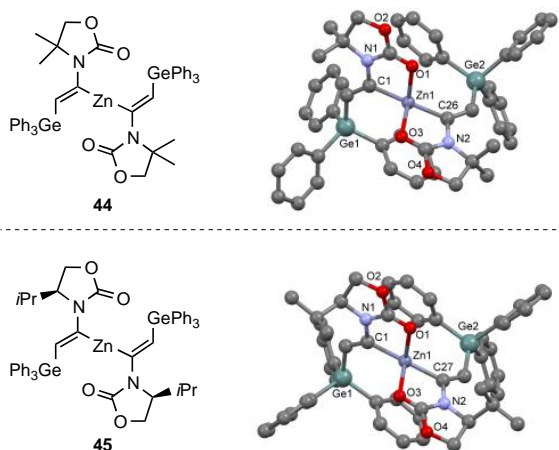
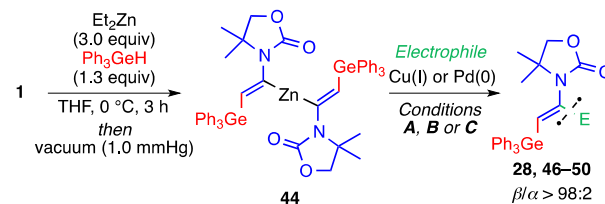


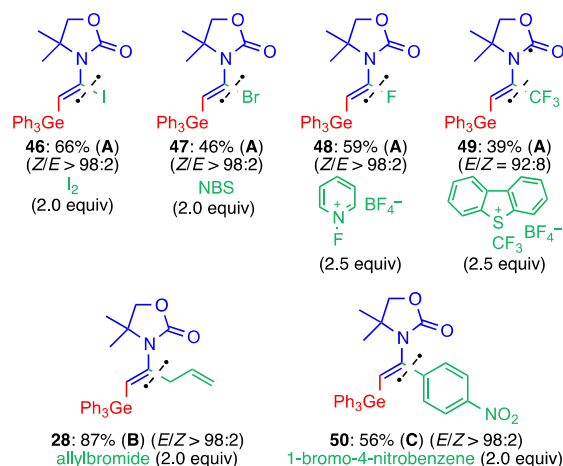
Figure 1. X-ray crystal structure of **44** and **45**. Selected bond lengths and bond angles. **44**: $\text{Zn}\text{-C}1 = 1.995(8)$ Å, $\text{Zn}\text{-C}26 = 1.985(8)$ Å, $\text{C}1\text{-Zn}\text{-C}26 = 170.8(3)^\circ$, $\text{O}1\text{-Zn}\text{-O}3 = 97.8(3)^\circ$. **45**: $\text{Zn}\text{-C}1 = 1.989(7)$ Å, $\text{Zn}\text{-C}27 = 2.009(7)$ Å, $\text{C}1\text{-Zn}\text{-C}27 = 165.5(3)^\circ$, $\text{O}1\text{-Zn}\text{-O}3 = 91.3(3)^\circ$.

The divinylzinc intermediates arising from the gerylzincation / evaporation sequence also underwent smooth $\text{Cu}(\text{I})$ -mediated electrophilic substitution in THF and this modified protocol offered additional possibilities for $\text{C}(\text{sp}^2)\text{-Zn}$ functionalization (Scheme 10). The use of halogen electrophiles was possible and β -germylenamides decorated in α -position with iodine (**46**), bromine (**47**) or fluorine (**48**) were prepared in acceptable yields. Trifluoromethylation with Umemoto's reagent to deliver **49** was also accomplished. An additional asset of this protocol was that it made possible the use of catalytic amounts of $\text{Cu}(\text{I})$ salt, as shown for the formation of **28** in 87% yield from **1** using 10 mol% CuTC to promote the allylation step. It was also feasible to perform Pd -catalyzed Negishi-type cross-coupling reactions, and **44** reacted with 1-bromo-4-nitrobenzene to afford arylated product **50** in 56% yield. Here, 24% of product *E*-**2** coming from the hydrolysis of unreacted **44** was also recovered. It is noteworthy, that no cross-coupling reaction occurred when 1-iodo-4-nitrobenzene was used under similar conditions.

Scheme 10. Ynamide Gerylzincation / $\text{Cu}(\text{I})$ - or $\text{Pd}(\text{0})$ -Mediated Electrophilic Substitution via Divinylzinc Intermediate **44**

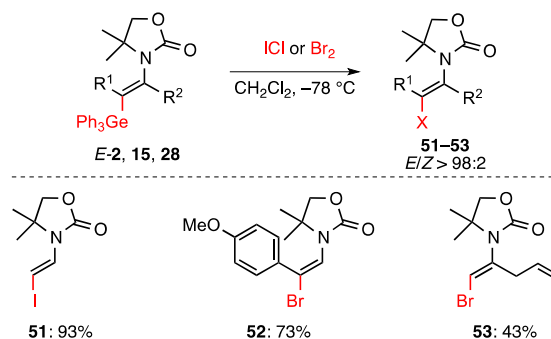


A: $\text{CuCN}\cdot 2\text{LiCl}$ (2.0 equiv), THF, -30 °C to 0 °C / rt
B: CuTC (10 mol%), THF, -30 °C to rt
C: Pd_2dba_3 (5 mol%), $(2\text{-Fur})_3\text{P}$ (10 mol%), THF, 65 °C



To illustrate the synthetic potential of the β -germylenamides accessible through the new gerylzincation chemistry, it was then demonstrated that they could be easily converted, with immaculate retention of the double bond geometry, into β -haloenamides that are valuable for further elaboration of stereodefined enamides.²⁹ Unlike for trialkylvinylgermanes, halodegermylation reactions of triphenylvinylgermanes are sluggish or ineffective.^{5b,d,e} Conversely, for β -triphenylgermylenamides, they were remarkably efficient (Scheme 11). Treatment at -78 °C in CH_2Cl_2 of *E*-**2** with ICl resulted in clean halodegermylation providing disubstituted iodoenamide **51** in 93% yield, while reaction of **15** and **28** with Br_2 led to trisubstituted bromoenamides **52** and **53** in 43–73% yields.

Scheme 11. Halodegermylation Reactions of β -Triphenylgermylenamides

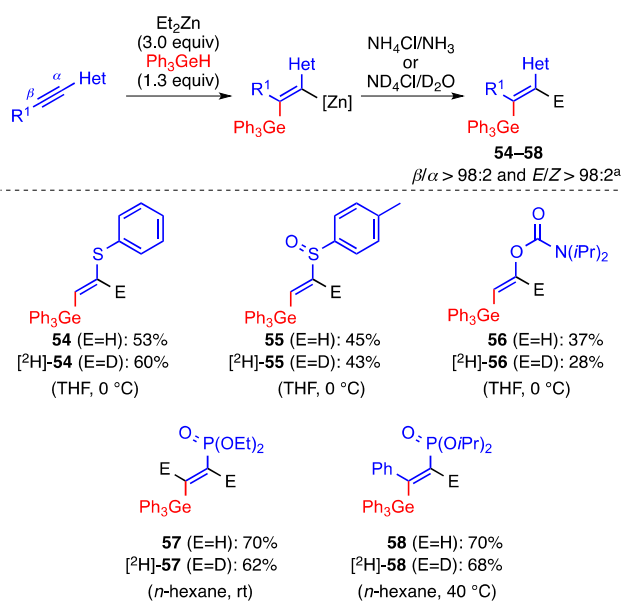


To finish our study, the possibility of performing the gerylzincation reaction with alkynes other than ynamides was considered. The addition of Ph_3GeH / Et_2Zn across the

carbon–carbon triple bond of sulfur-, oxygen-, and phosphorous-substituted terminal alkynes occurred at 0 °C yielding the corresponding β -heteroatom-substituted vinylgermanes **54–57** with full β -regio- and *cis*-stereocontrol (Scheme 12). It was interesting to note that the heteroatom substituent had no impact on the regioselectivity, as this trend differed from that observed for certain alkyne carbometalation reactions.⁶⁰ THF was generally the solvent of choice, but in the case of **57** better yields were obtained in *n*-hexane. Isolated yields were in the range 37% to 70%. Likewise, tri-substituted vinylgermane **58** was delivered in 70% yield (with the same regio- and stereocontrol) from the gerylzincation in *n*-hexane at 40 °C of an internal α -phosphonate-substituted alkyne. The *E* configuration of product **58** was established by X-ray crystallographic analysis.⁴³

In all cases, D-labeling confirmed the formation of vinylzinc intermediates and the availability of the C(sp²)–Zn bond formed for further elaboration, as [²H]-**54**–[²H]-**58** were obtained (> 90% D-incorporation) on quenching with ND₄Cl. In the case of product **57**, D-incorporation α to germanium was also observed indicating that here, gerylzincation occurred on the zincated alkyne.

Scheme 12. Gerylzincation of Other α -Heteroatom-Substituted Alkynes

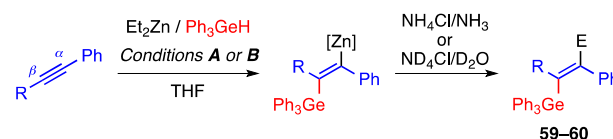


^aMeasured by ¹H NMR prior to purification.

To finish our study, we next established that the new gerylzincation approach was not restricted to α -heteroatom-substituted alkynes and could also be extended to conventional alkynes (Scheme 13). At 40 °C in THF, 1-phenyl-1-propyne and diphenylacetylene yielded products **59** and **60** in respectively 40% and 49% yield in high *trans*-stereoselectivity consistent with a radical chain-transfer mechanism with a Zn-atom transfer under kinetic control. Here, the intermediate vinyl radical (sp-hybridized as the result of the conjugation with the adjacent Ph ring) was expected to be linear, and Et₂Zn to approach from the less hindered side opposite to the bulky Ph₃Ge group.⁶¹ At this temperature however, the reactions did not proceed to completion, a behavior that was attributed to the shortening of the radical chains because of a less favorable radical addition step.⁶² This effect was eventually corrected by

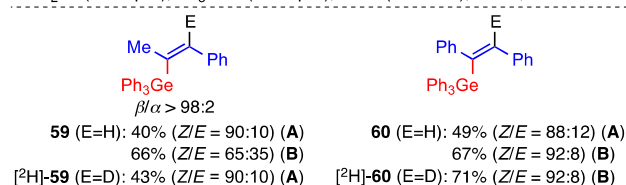
adding AIBN as radical initiator and operating at 80 °C to ensure its decomposition. Products **59** and **60** were obtained in improved 66% and 67% yields within much shorter reaction times (1 h). Control experiments in the absence of AIBN gave less than 10% conversion under the same operating conditions, what underscored the decisive role played by the radical initiator and provided further support for radical character of the gerylzincation. The stereoselectivity remained very high in the case of **60**, but dropped for **59** as the consequence of radical induced isomerization of the intermediate zincated vinylgermanes.⁶³

Scheme 13. Gerylzincation of 1-Phenyl-1-Propyne and Diphenylacetylene



A: Et₂Zn (3.0 equiv), Ph₃GeH (1.3 equiv), 40 °C, 16 h

B: Et₂Zn (3.0 equiv), Ph₃GeH (2.0 equiv), AIBN (25 mol%), 80 °C, 1 h



CONCLUSIONS

In conclusion, we disclosed here the first gerylzincation reaction of C–C triple bonds using a combination of a hydrogermane and diethylzinc in a radical chain process. Ready availability of the reagents, operational simplicity and excellent levels of regio- and stereocontrol are important aspects of this reaction that can be performed on terminal and internal ynamides as well as on other sulfur-, oxygen-, and phosphorous-substituted alkynes. The decisive feature of this new approach is the possibility of using the C(sp²)–Zn bond formed as linchpin for the subsequent installation of carbon or heteroatom substituents with complete retention of configuration through *in situ* Cu(I)- or Pd(0)-mediated electrophilic substitution. This offers a convenient and modular route to elaborated di-, tri- and tetrasubstituted vinylgermanes decorated with heteroatom substituents β to germanium that are useful for the preparation of stereodefined alkenes and cannot be prepared using hydrogermylation chemistry or previously reported gerylmatalation reactions.

As part of this work, we also were able to isolate and fully characterize, including by X-ray crystallography, the α -amino β -germyl vinylzinc intermediates arising from the gerylzincation of ynamides. These divinylzinc complexes showed exceptional stability towards oxidation and hydrolysis, probably as the result of the very uncommon seesaw coordination of zinc.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website.

Additional data and discussion, experimental details, NMR spectra for new compounds, and X-ray crystal structures (PDF)

Crystallographic information files (CIF)

AUTHOR INFORMATION

Corresponding Author

* alejandro.perez_luna@sorbonne-universite.fr

Author Contributions

All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

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ABBREVIATIONS

AIBN, azobisisobutyronitrile; CuTC, Copper(I)-thiophene-2-carboxylate; Me-THF, 2-methyltetrahydrofuran; MTBE, methyl *tert*-butyl ether; TEMPO, (2,2,6,6-tétraméthylpipéridin-1-yl)oxy; THF, tetrahydrofuran.

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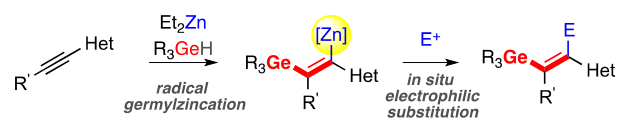
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- (43) Crystal structures were deposited at the Cambridge Crystallographic Data Centre with numbers CCDC 1862400 (**E-12**), 1862401 (**E-14**), 1862402 (**E-23**), 1862403 (**Z-25**), 1862404 (**E-40**), 1862405 (**44**), 1862406 (**45**) and 1862407 (**E-58**) and can be obtained free of charge via www.ccdc.cam.ac.uk.
- (44) In the absence of Ph₃GeH, metalation of **1** by Et₂Zn (3.0 equiv) was nevertheless observed both in *n*-hexane (35% after 1 h 40 min at 0 °C) and in THF (43% after 3 h at 0 °C).
- (45) It is established that radical hydrogermylation of terminal alkynes with Ph₃GeH can occur to variable extents in the absence of added radical initiators, see ref 15, 16e and 17b.
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- Het = [N], [S], [O], [P]; E = [C], [S], I, Br, F, CF₃
- high regio- and diastereoselectivity
- modular access to di-, tri-, and tetrasubstituted vinylgermanes
- > 50 examples
- functionalization of C(sp²)-Ge bond possible

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