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An Experimental and Theoretical Study of the Mechanism of Stannylcupration of α,β-Acetylenic Ketones and Esters

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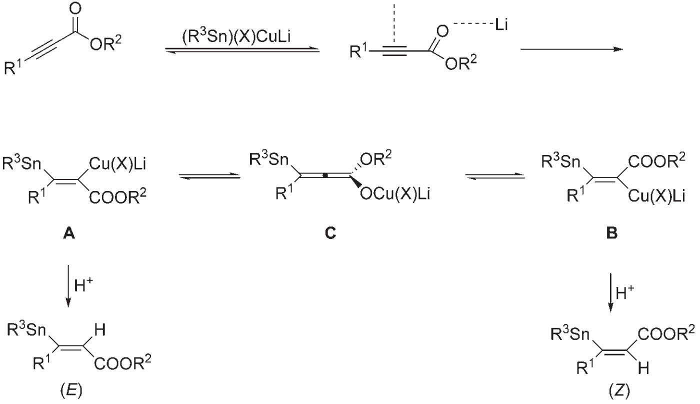
Abstract: The title reaction has been investigated by experimental and computational (DFT) techniques, and subsequently compared to the corresponding carbocupration reaction, with particular emphasis on the stereoselectivity. For stannylcupration of an ynone substrate, only the *anti*-addition product is observed, whereas for the corresponding ynoate substrate, the stereoselectivity can be affected by the reaction conditions: in the presence of methanol as proton donor, the initial *syn*-addition product can be trapped, whereas a *syn*/*anti* mixture is obtained in a non-protic solvent. This is in sharp contrast to the carbocupration of the same ynone substrate with a cyanocuprate (RCu(CN)Li), which is highly selective for *syn*-addition. The product selectivities can be understood from a detailed computational characterization of the reaction paths, and in particular from the relative stabilities of the vinyl cuprate and allenolate intermediates. It is suggested that the stereodetermining step is protonation of vinyl cuprate intermediates.

Keywords: alkynes · cuprates · density functional calculations · stannylcupration · stereoselectivity

Introduction

Heteroatomcuprates, especially stannylcopper and silylcopper species, are versatile reagents for organic synthesis.[1] For example, trialkylstannyl cuprates, $(R_3Sn)(X)_nCuLi_n$, react with a wide range of organic substrates, particularly alkynes. This stannylcupration process provides convenient entry to structurally diverse alkenyl stannanes which are themselves very useful building blocks for further elaboration, including the formation of vinyllithiums and vinyl iodides or as coupling partners in the Stille reaction.[2] The pioneering work of Piers[3] on the stannylcupration of α,β-acetylenic esters, which has been extended to α,β-acetylenic *N*,*N*-dimethylamides[4] and α,β-acetylenic acids,[5] provides highly stereoselective routes to either (*E*)- or (*Z*)-β-stannylated α,β-unsaturated moieties, by simple variation of the reaction conditions (Scheme 1).



Scheme 1. Proposed mechanism for addition of stannylcuprates to α,β-acetylenic esters (adapted from ref. [3a]).

For α,β-acetylenic esters, the reaction has been envisioned to occur via regio- and stereoselective addition across the triple bond to give **A** which, if protonated under kinetic conditions (the ester is mixed in THF with an alcohol as a proton source prior to exposure to the cuprate at −78 °C), gives mainly or exclusively (up to >99:1 selectivity) the *E* isomer. Warming the reaction mixture to ca. −50 °C before the addition of a proton source provides the thermodynamically more stable *Z* isomer (typically around 98:2 selectivity) after equilibration to **B** via the allenolate **C**.

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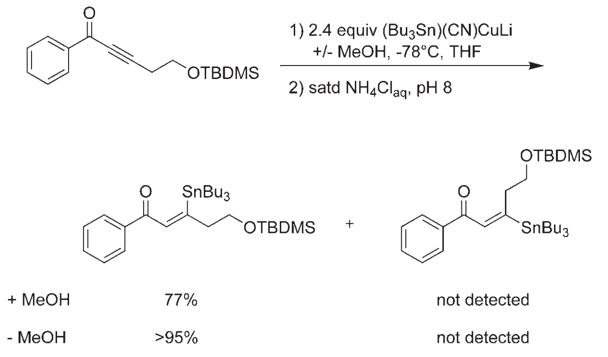
Recently, as part of a total synthesis project,[6] we became interested in the development of synthetic methodology enabling the stereoselective production of (*E*)-β-trialkylstannyl α,β-unsaturated ketones. Based on analogy with the work of Piers, the obvious route would be regio- and stereoselective stannylcupration of the corresponding α,β-acetylenic ketones, and we were surprised to find only one report[7] of such a reaction being used in the context of total synthesis. Accordingly, we screened a range of stannylcupration reactions of various acetylenic ketones with different combinations of solvent, reaction temperature, stannylcuprate and proton source.[8] To our surprise, in all these experiments the (*Z*)-β-trialkylstannyl α,β-unsaturated ketones were consistently formed as the major product in high yield and with excellent stereoselectivity ($>95\%$), often without even a trace of the *E* isomers, as exemplified in Scheme 2.



Scheme 2. High *Z* selectivity in the stannylcupration of alkynones, both in the presence and absence of methanol (taken from ref. [8]).

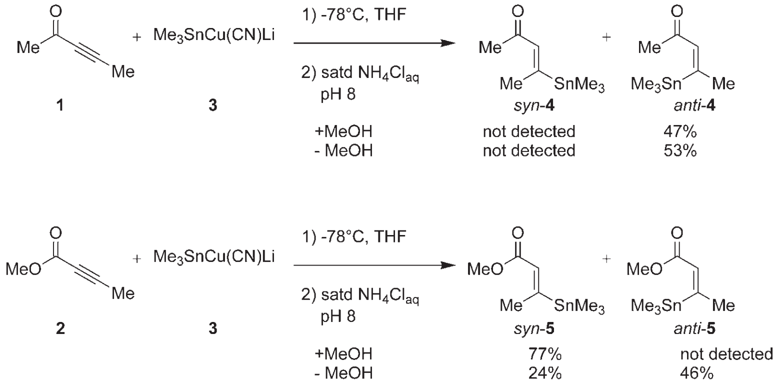
There is thus a very different reactivity/selectivity pattern for the stannylcupration of α,β-unsaturated alkynoic esters and ketones, respectively, We also noted that (in line with the work of others[9]) the corresponding reactions of the Gilman or Lipshutz organocuprates with our alkynones were non-stereoselective,[8] thus providing more food for mechanistic thought. Important mechanistic studies of this type of reaction, involving the "classical" organocuprates, have been reported by Ullenius[10] and Krause,[11] while Nakamura[12] has recently contributed with extensive computational studies; Hall[13] has made a systematic study of the effect of additives on the stereochemical outcome of the reaction involving acetylenic esters. In detailed NMR studies of the carbocupration of α,β-acetylenic substrates, Ullenius[10] noted distinct differences between the behavior of ynoates and ynones, the latter forming only allenolates as observable intermediates (corresponding to **C** in Scheme 1) which are subsequently protonated with only low (or no) stereoselectivity. This further prompted the question as to why the stannylcupration reactions of alkynones are so highly stereoselective. A possible answer to that question, and an explanation of the different reactivity/selectivity pattern of alkynones versus alkynoates in stannylcupration reactions, is the subject of this report.

Results

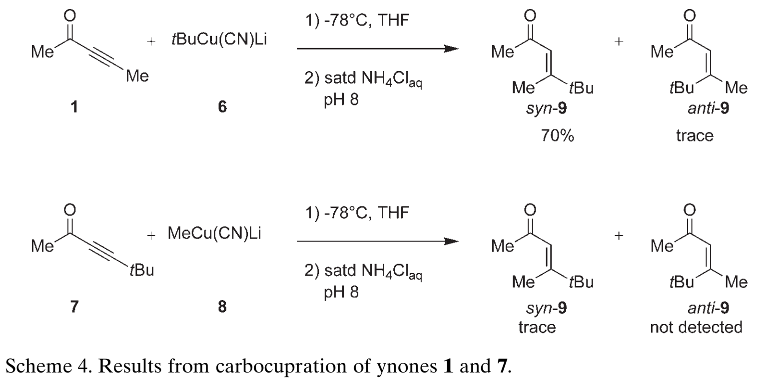
Experimental results

A model system was chosen to be as simple as possible to facilitate a study by both experimental and computational methods. Therefore, the ketone chosen here was pent-3-yn-2-one (**1**), the ester methyl 2-butynoate (**2**), and the stannylcuprate $Me_3SnCu(CN)Li$ (**3**). The reactions were performed in THF at −78°C in the presence (+MeOH) or absence (−MeOH) of methanol as proton source. When performed in absence of methanol the reaction mixture was worked up with saturated aqueous ammonium choride (Scheme 3).

To parallel the stannylcupration with the related carbocupration, **1** was subjected to the corresponding carbocuprate *t*BuCu(CN)Li (**6**). The opposite substitution pattern was also investigated to probe the influence of the sterics of the acetylene substituent and the carbocuprate. Therefore the *t*Bu-substituted alkyne **7** was treated with the carbocuprate MeCu(CN)Li (**8**). In both cases the reaction mixtures were worked up with saturated ammonium chloride. The results are presented in Scheme 4.



Scheme 3. Stannylcupration of ynone **1** and ynoate **2**.



Scheme 4. Results from carbocupration of ynones **1** and **7**.

Under these conditions the cuprate **8** surprisingly proved to be very unreactive towards **7**, and after three hours of reaction most of the starting material was recovered. This is possibly due to formation of less reactive clusters of reagent **8**, a factor which is not an issue for the cuprate **6**.[14]

Computational results

Stannylcupration of pent-3-yn-2-one: The starting point for the calculations is the complex **10**, which has been shown by experimental and computational methods to be the initially formed complex when ynones/ynoates are reacted with cuprates.[10,12b] This can be viewed as being either a copper(III) species, or a copper(I) coordinated to an alkyne (Figure 1). We have chosen the copper(III) description since it is more in line with the calculated geometry of intermediates **10** and **15**.

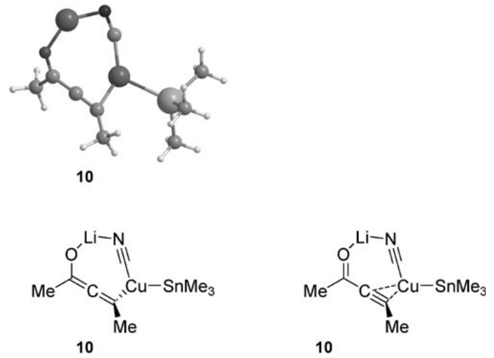


Figure 1. Calculated structure of the "Cu^{III}"-complex **10**.

The Cu^{III} species **10** can undergo a reductive elimination type reaction in which the carbon–tin bond is formed via the transition state **11ts**, with a low barrier of 13 kJ mol^{-1} (Figure 2). After the carbon–tin bond is formed the complex collapses to an allenolate intermediate **12**, in which the Cu^{I} is coordinated to the α,β-double bond. The reaction path was confirmed by a relaxed scan of the C–Sn distance, as well as by displacement followed by energy minimization, in both cases yielding the allenolate **12**. We note that this mechanism is different from the one proposed for the carbocupration of ynones, in which the reductive elimination of the Cu^{III} species always leads to a vinylcuprate type structure.[12b]

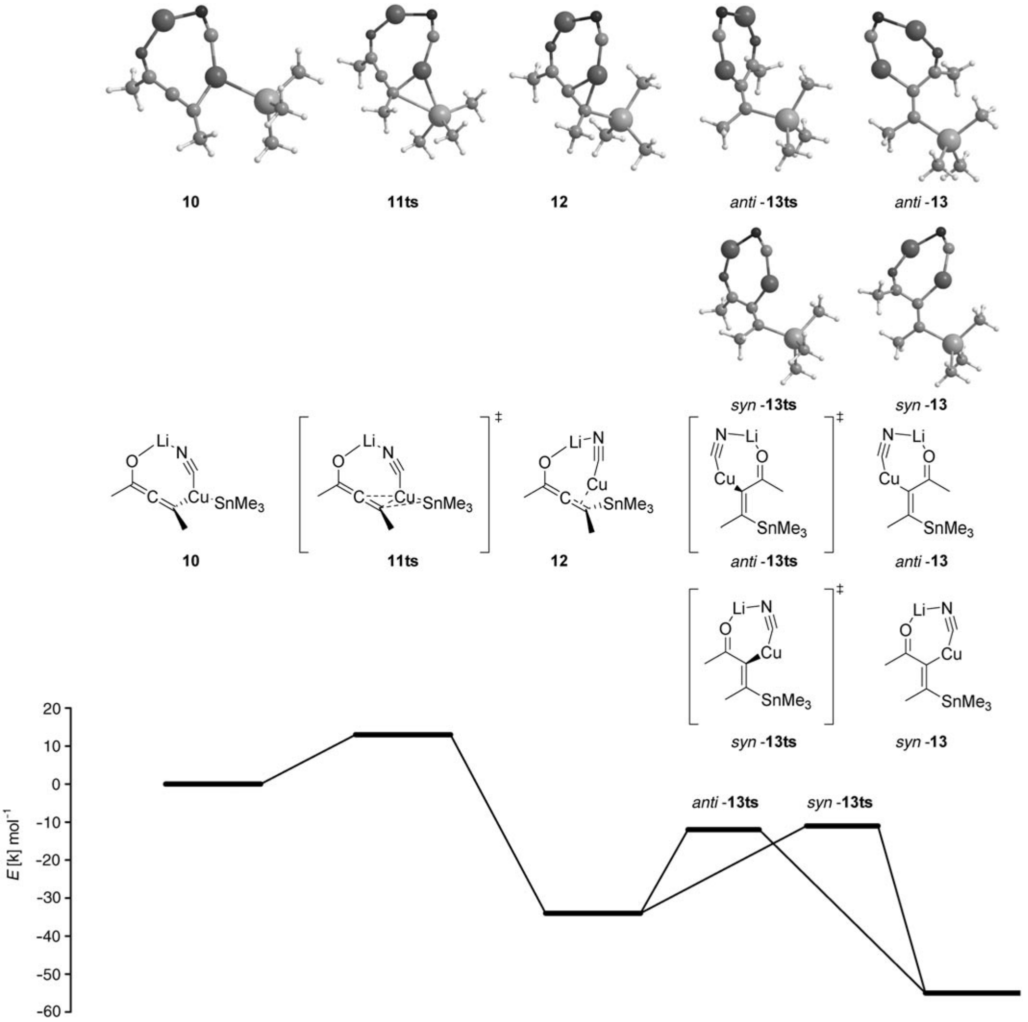


Figure 2. Energy profile for stannylcupration of ynone **1**.

Isomerizations of the allenolate **12** to the *syn*-addition vinylcuprate *syn*-**13** or the *anti*-addition vinylcuprate *anti*-**13** occur via basically identical barriers, 22 kJ mol^{-1} for *syn*-**13ts** and 23 kJ mol^{-1} *anti*-**13ts**. The resulting vinylcuprates *syn*-**13** and *anti*-**13** are isoenergetic, and the overall reactions from **10** (Cu^{III} complex) are calculated to be exothermic by 55 kJ mol^{-1} (Figure 2). The energy required for isomerization between *syn*-**13** and *anti*-**13** is thus calculated to be 44 kJ mol^{-1}, with the allenolate intermediate **12** being 21 kJ mol^{-1} less stable than the vinylcuprates.

Since the reaction is conducted in THF it is possible that the lithium ion is dissociated to yield an anionic vinylcuprate intermediate, in analogy with earlier observations for lithium dialkylcuprates,[15] which then is protonated to yield the products. Due to the stabilizing effect of an oxygen–tin (Lewis base/Lewis acid) interaction the *anti*-addition complex *anti*-**14** is calculated to be stabilized by as much as 30 kJ mol^{-1} in the gas phase, relative to the *syn*-addition complex *syn*-**14** (Figure 3). In the *syn*-addition complex there is also a destabilizing interaction between the carbonyl oxygen and the anionic copper. Calculations with a solvation model were therefore performed. These yielded a difference of 22 kJ mol^{-1} in favor of *anti*-**14**. Thus only in the presence of Li$^+$ ions are the *syn* and *anti* intermediates isoenergetic, and decomplexation leads to a preference for the complex leading to the *anti*-addition product.

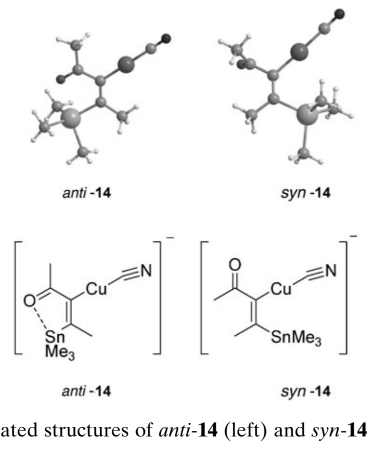


Figure 3. Calculated structures of *anti*-**14** (left) and *syn*-**14** (right).

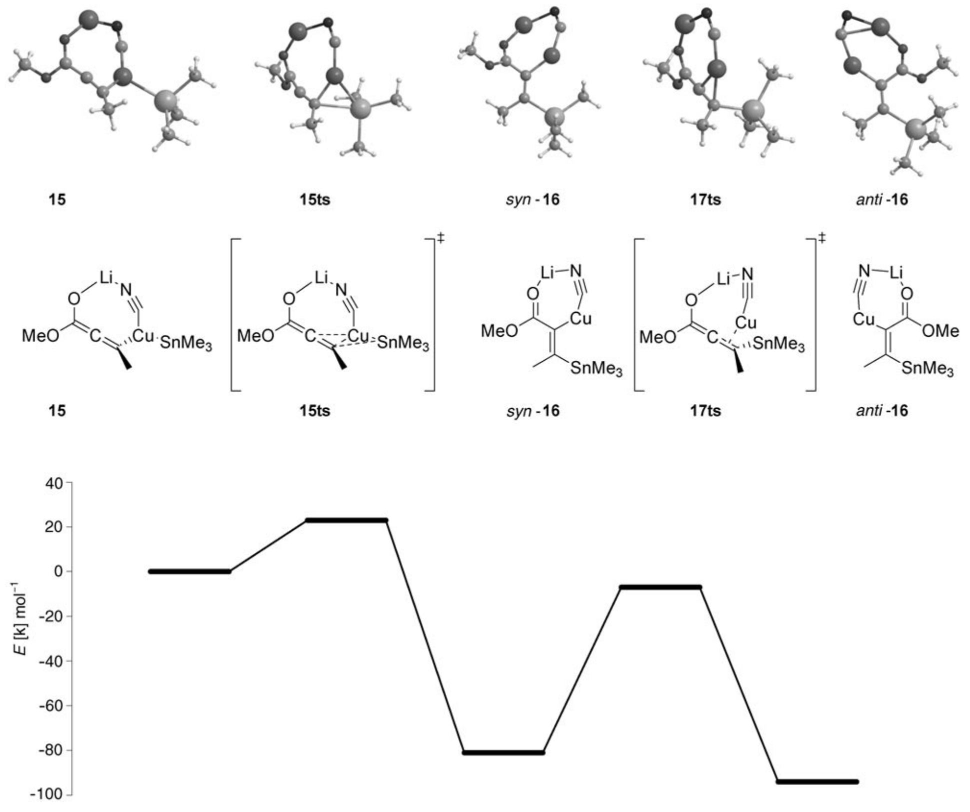


Figure 4. Energy profile for stannylcupration of ynoate **2**.

Stannylcupration of methyl-2-butynoate: Cu^{III}-complex **15** analogous to **10** was the starting point for the mechanistic study of the stannylcupration of methyl-2-butynoate (Figure 4). This complex can undergo reductive elimination to yield the *syn*-addition vinylcuprate *syn*-**16**. The mechanism is analogous to the one for carbocupration of ynones/ynoates proposed by Nakamura et al.,[12b] and proceeds with a barrier which is calculated to be slightly higher than for the reaction of pent-3-yn-2-one described above (23 kJ mol^{-1}) and the overall reaction is exothermic by 81 kJ mol^{-1}. This complex can then rearrange to isomeric vinylcuprate *anti*-**16**, via an allenolate type transition state **17ts** with a barrier of 74 kJ mol^{-1}. From **15** the overall reaction is exothermic by 94 kJ mol^{-1}. It is the stabilizing oxygen–tin (Lewis base/Lewis acid) interaction in the *anti*-addition vinylcuprate *anti*-**16** that makes it more energetically favorable than the *syn*-addition vinylcuprate *syn*-**16**.

Another *anti*-addition vinylcuprate complex (**18**) was also found in which the ester moiety had been rotated 180° (Figure 5). This complex was calculated to be less stable than *anti*-**16** by 39 kJ mol^{-1}.

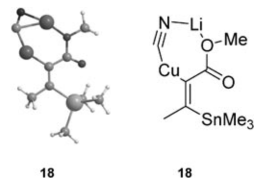


Figure 5. Calculated structure of **18**, a less stable isomer of *anti*-**16**.

Carbocupration of ynones: Carbocupration of pent-3-yn-2-one (**1**) by *t*BuCu(CN)Li **6** has been investigated for comparison with the stannylcupration (Figure 6). The reaction starts with a Cu^{III} species analogous to the ones described above for the stannylcuprations. The complex **19** formed from **1** and **6**, undergoes reductive elimination to yield the vinylcuprate *syn*-**21** with a barrier of 39 kJ mol^{-1} (**20ts**). *syn*-**21**, the initially formed intermediate in the reaction between **1** and **6**, isomerizes to the allenolate **22** with a barrier which is only slightly above the energy of **22** (0.1 kJ mol^{-1}). Formation of **22** is endothermic by 33 kJ mol^{-1}. The transition state for formation *anti*-**21** (*anti*-**23ts**) is also low, 0.4 kJ mol^{-1}, and the overall reaction from the vinylcuprate *syn*-**21** to the isomeric vinylcuprate *anti*-**21** is calculated to be endothermic by 9 kJ mol^{-1} (Figure 6). This difference in potential energy of the two intermediates is due to the unfavorable steric interaction between the *tert*-butyl group and the methyl group bonded to the carbonyl in *anti*-**21**. The favorable Lewis acid/Lewis base interaction in the analogous stannylcupration intermediates has no counterpart in the carbocupration case. This important feature will be discussed in more detail below.

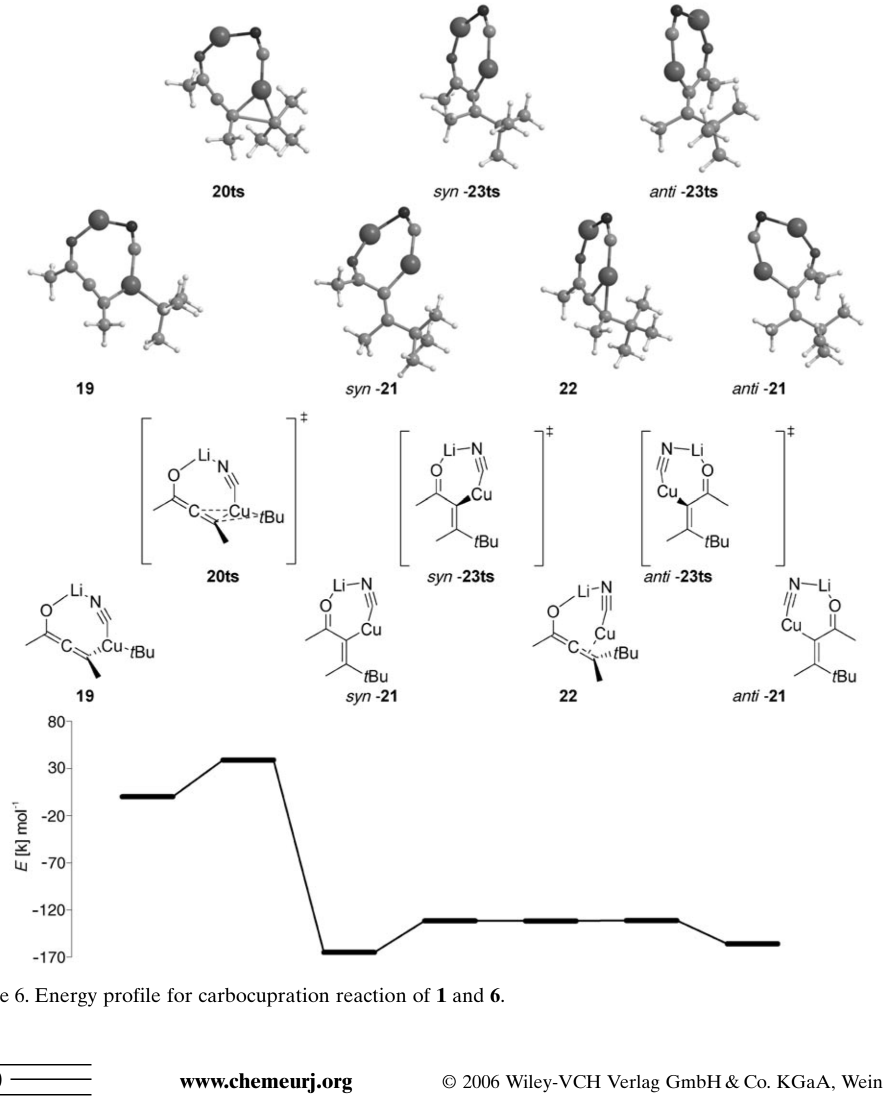


Figure 6. Energy profile for carbocupration reaction of **1** and **6**.

Discussion

The observed stereochemical outcome of the stannylcupration of ketones was at first surprising. Previous observations have shown stannylcupration of esters to yield *syn*-addition products at low temperature.[3] The stereochemical outcome of our model system, ketone **1** and stannylcuprate **3**, was always the *anti*-addition product *anti*-**4**, independent of both the quenching temperature and the nature of the proton source.

Previous investigations of the related carbocupration of ynones and ynoates made a link between the conjugate addition and insertion of the triple bond into the Cu–C bond.[12b] It was shown that the carbon–carbon bond is formed in a reductive elimination from a copper(III) species, after which the complex collapsed to the alkyne *syn*-insertion vinylcuprate analogous to *syn*-**21**. In the present study another mechanism has been observed for the stannylcupration of ynones. Also here the initial complex formed is a Cu^{III} species **10** (Figure 2). Reductive elimination from this complex takes place via a low energy transition state **11ts**, with a calculated barrier of merely 13 kJ mol^{-1}. From here the mechanism of the stannylcupration differs from the one found for the carbocupration. After **11ts** the complex does not form a *syn*-addition vinylcuprate but instead the allenolate **12**. This has some fundamental consequences for the expected outcome of the reaction. Whereas one would expect pure *syn*-addition products at low temperature for carbocuprations and a mixture when performed at higher temperatures, the stannylcupration reaction would be expected to yield mixtures even at low temperature since the initial intermediate **12** could in principle yield both products, either by direct protonation of **12** or protonation of the vinylcuprates *syn*-**13** and *anti*-**13**. Formation of *syn*-**13** and *anti*-**13** takes place via similar barriers and the two isomers are calculated to be isoenergetic, wherefore direct protonation of the isomers of **13** would be expected to lead to a mixture of stereoisomeric products. We are thus left with two possible rationalizations for the experimentally observed stereochemical outcome of the reaction. The first is that the species which is protonated is the allenolate **12**. The steric bulk of the stannyl group could then hinder the protonation which would yield the *syn*-addition product **4**, while protonation from the other side would yield the observed product. The other possibility is that the complexes which are protonated are not the isomers of **13**, but instead those in which the lithium ion has dissociated to give *syn*-**14** and *anti*-**14** (Figure 3). Of these, *anti*-**14** is strongly favored (30 kJ mol^{-1} in the gas phase) due to a strong Lewis acid/Lewis base interaction between the tin and the carbonyl oxygen, and direct protonation of *anti*-**14** would lead to the observed product.

While the stereochemical outcome of the stannylcupration of ynone **1** was surprising, the product distribution of the corresponding reaction between **3** and ynoate **2** followed literature precedence.[3] Protonation at low temperature results in only *syn*-addition product and at higher temperature a mixture of *syn*- and *anti*-addition products. The computational investigation of the stannylcupration of ynoate **2** by stannylcuprate **3** starts with the Cu^{III}-complex **15** (Figure 4) from which reductive elimination of the stannyl group and the β-carbon of the ynoate occurs with a calculated barrier of 23 kJ mol^{-1} which is only slightly higher than for the corresponding reaction at **10**. From here the reaction takes a different path compared with the ynone reaction, and the product of the reductive elimination is the *syn*-addition vinylcuprate *syn*-**16**, which can then isomerize to *anti*-**16**. For this reaction no allenolate intermediate was found but instead a transition state **17ts** with an allenolate type structure. The energy required for this isomerization was found to be 74 kJ mol^{-1} which is substantially higher than for the corresponding reaction of the ynone (44 kJ mol^{-1}). Due to a stabilizing interaction between the alkoxy oxygen and the tin atom, *anti*-**16** is stabilized relative to *syn*-**16** by 13 kJ mol^{-1}. These results are in agreement with the experimental observations that at low temperature the kinetic product *syn*-**5** is formed in 77 % yield, while in the case where the reaction is quenched with aqueous ammonium chloride (thus increasing the temperature), both the kinetic product *syn*-**5** and the thermodynamic product *anti*-**5** are observed, in 24 and 46 % percent yields, respectively.

The corresponding carbocupration reaction between **1** and **6** resulted in formation of the *syn*-addition product *syn*-**9** exclusively (Scheme 4), in sharp contrast to the *anti*-addition observed in the stannyl cupration reaction between **1** and **3** (Scheme 3). Our carbocupration results with cyanocuprate **6** are also in sharp contrast to earlier studies where mixtures were obtained when ynoates were reacted with Gilman or Lipshutz reagents.[8–10] Mechanistically the reaction is found to be similar to the one reported by Nakamura and co-workers for carbocuprations with the cuprate Me$_2$CuLi.[12b] The Cu^{III}-species **19** (Figure 6) reductively eliminates via the transition state **20ts**, which then collapses to the vinylcuprate *syn*-**21**. *syn*-**21** can isomerize to *anti*-**21** via the allenolate intermediate **22**. Energetically, the most favorable of the two vinylcuprates is *syn*-**21** (by 9 kJ mol^{-1}), due to a steric interaction between the tert-butyl group and the α protons in *anti*-**21**. The allenolate **22** via which the isomerization between the vinylcuprates occurs, is 33 kJ mol^{-1} higher in potential energy than *syn*-**21**. The transition states *syn*-**23ts** and *anti*-**23ts** are slightly higher than **22** in potential energy (0.1 and 0.4 kJ mol^{-1}, respectively). An intermediate flanked by such low energy barriers should not be considered a true minimum, but rather a transient point on the potential energy surface, but the energy is still indicative of the barrier the molecule must pass over during isomerization of the vinylcuprates.

Carbocupration reagent **6** was originally chosen for its steric similarity to stannylcupration reagent **3**, and yet, the stereochemical outcome of their reactions with ynone **1** were completely different (Schemes 3 and 4). As mentioned above there are two possibilities for the origin of the stereochemistry, the first being stereoselective protonation of the allenolate intermediate where protonation on the same face as the bulkier group would be hindered (Figure 7). The second possibility is then protonation of the more stable vinylcuprate (Figure 8), which assumes a rapid equilibrium between the two isomers.

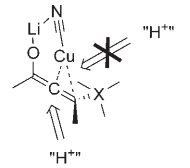


Figure 7. Selective protonation of allenolate (X = Sn or C).

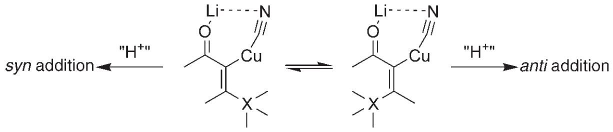


Figure 8. Protonation of the more stable vinylcuprate (X = Sn or C).

If the stereochemistry is set by selective protonation of an allenolate intermediate the outcome would be expected to be the same in both stannyl- and carbocupration. However the experimental results show that this it not the case: carbocupration of **1** yields the *syn*-addition product whereas the stannylcupration of one yields the *anti*-addition product (Schemes 3 and 4). It is thus likely that in both cases the species being protonated are the vinylcuprate intermediates, and that the stereochemistry is determined by the relative stability of these. For the carbocupration reaction the calculations are in good agreement with the experiments, *syn*-**21** that would lead to *syn*-**9** is energetically more favorable than *anti*-**21** by 9 kJ mol^{-1} (Figure 6). For the stannylcupration of **1** the situation is slightly more complex. Since the two vinylcuprates *syn*-**13** and *anti*-**13** in which the lithium ion is still coordinated have been calculated to be isoenergetic, another explanation is needed to rationalize the stereochemistry. The reaction is conducted in THF and therefore it is possible that the lithium ion is dissociated from the vinylcuprate intermediate. This yields the two anionic complexes *syn*-**14** and *anti*-**14**, where *anti*-**14** (which would lead to the observed product upon protonation) is found to be 30 kJ mol^{-1} more stable (22 kJ mol^{-1} with a solvent model). That *anti*-**14** is strongly favored is due to the interaction between the carbonyl oxygen and the stannyl moiety. The real situation may well be intermediate between the two sets of gas-phase calculations. Even if the lithium ion is still associated in solution, it will be at least partially solvated, bringing the system closer to model **14** than to **13**, and thus into good agreement with the experimentally observed selectivity.

The stereochemical outcome of the stannylcupration of ynoate **2** is in agreement with the computational results. When the protonation occurs at low temperature the only product observed is the kinetic product *syn*-**5**, while when the protons are added as an aqueous solution, and thus the temperature is increased, both the thermodynamic (*anti*-**5**) and the kinetic (*syn*-**5**) products are observed.

Conclusion

A difference in the stereochemical outcome between stannylcupration of ynones and ynoates has been observed, as well as a difference between stannylcupration and carbocupration of ynones. The mechanisms for the transformations have been studied by DFT methods. Combination of the experimental observations and the computational results has led to a rationalization of the differences in mechanism that give rise to the different product distributions. Firstly, the mechanism for the stannylcupration of ynones has been found to be different from the one suggested for carbocuprations. The stereochemical outcome was found to be due to a vinylcuprate intermediate with an interaction between the carbonyl oxygen and the stannyl group. Due to a low barrier for the interconversion between the two vinylcuprate isomers the reaction yields only the thermodynamic product, even at −78 °C. Secondly, the outcome of stannylcupration of ynoates was rationalized to be due to a mechanism in which the kinetic vinylcuprate intermediate is first formed. The barrier for isomerization to the thermodynamic vinylcuprate is large enough for this not to occur at −78 °C, but at higher temperature both the products from the thermodynamic and kinetic intermediates were observed. Thirdly, the carbocupration of ynone **1** was found to yield the opposite product compared to the stannylcupration. This strongly suggests that the stereochemical outcome of these reactions is determined by the relative stabilities of the vinylcuprates, rather than by stereoselective protonation of the allenolate intermediates.

Experimental Section

General methods: ^{1}H (500 MHz) and ^{13}C (125 MHz) NMR spectra were recorded by using $CDCl_3$ as the solvent, and signal positions (δ values) were measured relative to the signals for $CHCl_3$ (7.27) and $CDCl_3$ (77.0), respectively. Tin–hydrogen coupling constants, J(Sn,H), are given as the average of the ^{117}Sn and ^{119}Sn values. IR spectra were obtained for thin films on AgCl plates, and only the strongest/structurally most important peaks (ν_{max}/cm^{-1}) are listed. HRMS was performed at the Department of Chemistry, University of Copenhagen, Denmark. Molecular mass determinations (high-resolution mass spectrometry) for substances containing Me_3Sn are based on ^{120}Sn and made on $[M{-}R]^+$. All compounds on which HRMS were performed exhibited clean ^{1}H NMR spectra and showed one spot on TLC analysis. TLC analyses were performed on Merck aluminum-backed F254 silica gel plates using UV light, and a solution of 5–10 % phosphomolybdic acid for visualization. All chromatography was performed with the use of Merck silica gel (40–63 µm).Prior to use, THF was distilled under nitrogen from Na/benzophenone. Commercially available compounds were used as received unless otherwise indicated. Saturated ammonium chloride (pH~8) was prepared by addition of aqueous ammonia (25 %; 60 mL) to saturated ammonium chloride (950 mL). Commercial copper(I) cyanide was oven-dried overnight at 150 °C and used without further purification. All reactions were carried out under an atmosphere of dry argon in carefully flame-dried glassware and Schlenk tubes, rigorously excluding oxygen from the reaction mixture. Argon gas was dried by passage through phosphorus pentoxide and silica gel.

General procedure for stannylcupration of α,β-acetylenic ketone and ester: A solution of hexamethylditin (328 mg, 1.0 mmol) in THF (9 mL) was cooled to −20 °C and methyllithium (1.4 M in Et_2O, 0.7 mL, 1.0 mmol) was added dropwise via syringe, and stirring was continued at −20 °C for 15 min to afford a pale yellow solution of trimethylstannyllithium. The mixture was cooled to −78 °C and solid copper(I) cyanide (90 mg, 1.0 mmol) was added in one portion. After 10 min of stirring, the reaction mixture was heated to −45 °C for 10 min to afford a bright orange solution of lithium (cyano)(trimethylstannyl)cuprate. The reaction mixture was cooled to −78 °C before dropwise addition of pent-3-yn-2-one or methyl propiolate (0.33 mmol) in THF (1 mL). The reaction mixture was monitored by TLC, and when all starting material had reacted the reaction was quenched by addition of saturated ammonium chloride (pH~8). The organic phase was washed with brine, dried over magnesium sulfate, and filtered. The solvent was evaporated and the residue purified by flash column chromatography on silica gel (hexane/ethyl acetate) to give the stannylcupration products as colorless oils.

Addition of MeOH: Following the general procedure, with the modification that MeOH (0.6 mmol) and the acetylenic substrate (0.33 mmol) dissolved in the same THF solution (1.0 mL) were added dropwise to the stannylcuprate reaction mixture.

Analytical data for products

(*Z*)-4-(Trimethylstannyl)-pent-3-en-2-one: ^{1}H NMR (500 MHz, $CDCl_3$): δ = 6.85 (m, J(Sn,H) = 120 Hz, 1 H), 2.21 (s, 3 H), 2.16 (d, J = 2, J(Sn,H) = 46 Hz, 3 H), 0.13 (s, J(Sn,H) = 55 Hz, 9 H); ^{13}C NMR (125 MHz, $CDCl_3$): δ = 197.4, 172.8, 136.0, 29.9, 26.7, −7.8; IR (neat): $\tilde{\nu}$ =2967, 1682, 1575, 1431, 1358, 1198 cm^{-1}; HRMS (EI): m/z: calcd for $C_7H_{13}OSn$: 232.9990, found 232.9995 $[M{-}CH_3]^+$.

(*Z*)-3-(Trimethylstannyl)but-2-enoic acid methyl ester: ^{1}H NMR (500 MHz, $CDCl_3$): δ = 6.40 (m, J(Sn,H) = 118 Hz, 1 H), 3.72 (s, 3 H), 2.15 (d, J = 2, J(Sn,H) = 45 Hz, 3 H), 0.18 (s, J(Sn,H) = 55 Hz, 9 H); ^{13}C NMR (125 MHz, $CDCl_3$): δ = 171.8, 168.2, 128.6, 51.4, 26.9, −7.8; IR (neat): $\tilde{\nu}$ = 2950, 1706, 1602, 1435, 1324, 1202 cm^{-1}; HRMS (EI): m/z: calcd for $C_7H_{13}O_2Sn$ 248.9939, found 248.9943 $[M{-}CH_3]^+$.

(*E*)-3-(Trimethylstannyl)but-2-enoic acid methyl ester: ^{1}H NMR (500 MHz, $CDCl_3$): δ = 5.99 (m, J(Sn,H) = 74 Hz, 1 H), 3.69 (s, 3 H), 2.39 (d, J = 2, J(Sn,H) = 50 Hz, 3 H), 0.18 (s, J(Sn,H) = 54 Hz, 9 H); ^{13}C NMR (125 MHz, $CDCl_3$): δ = 168.6, 164.8, 127.4, 50.7, 21.4, −10.0; IR (neat): $\tilde{\nu}$ = 2949, 1718, 1601, 1433, 1344, 1174 cm^{-1}; HRMS (EI): m/z: calcd for $C_7H_{13}O_2Sn$: 248.9939, found 248.9935 $[M{-}CH_3]^+$.

General procedure for carbocupration of α,β-acetylenic ketone: A mixture of CuCN (90 mg, 1 mmol) in THF (10 mL) was cooled to −40 °C. To the mixture was added alkyl lithium (1 mmol) carefully with stirring. The solution was then stirred at −40 °C for 15 min, and was then cooled to −78 °C, whereafter a solution of the ynone in 1 mL THF was added dropwise. After 10 min of stirring at −78 °C the reaction was quenched by addition of saturated ammonium chloride. The organic phases were separated and the aqueous phase was extracted with Et_2O. The combined organic phases were washed with saturated ammonium chloride and brine, dried over $MgSO_4$ and evaporated to dryness. The crude product was purified by flash chromatography.

Analytical data for 4,5,5-trimethyl-3-hexen-2-one: ^{1}H NMR (500 MHz, $CDCl_3$): δ = 6.13 (m, 1H), 2.19 (s, 3H), 2.10 (s, 3H,), 1.10 (s, 9H). These data are in agreement with literature values.[16] The stereochemistry was further confirmed by NOESY experiments.

Computational details: To include both steric interactions as well as the correct electronics the complete system has been investigated. All calculations were performed with the Jaguar 4.2 build 77 program package[17] using the hybrid functional B3LYP. The basis set used was the LACVP* which applies the 6-31G* for all light elements and the Hay–Wadt ECP and basis set for copper and tin.[18] To simulate solvent the Poisson-Boltzmann self consistent reaction field (PB-SCRF) incorporated in Jaguar 4.2 was used.[18] PB-SCRF is a continuum solvation model, where the molecule is put into a reaction field consisting of surface charges on a solvent accessible surface constructed using a hypothetical spherical solvent probe molecule with the indicated radius. The wavefunction and the reaction field charges are solved iteratively until self-consistency is reached. The parameters for the solvent have been set to $\varepsilon = 7.43$, probe radius = 2.52372 to simulate THF. All transition state structures were confirmed to have one negative frequency. The reaction path from **11ts** was checked by two methods. The first involved gradual decrease of the C–Sn distance by steps of 0.1 Å, fully relaxing all other coordinates at each point, starting with the Cu^{III}-species **10**. In the second method the transition state structure **11ts** was moved in the direction of the imaginary vibration and then minimized with a small trust radius. Both methods led to the allenolate structure **12**.

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