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# Base-catalyzed addition of silylacetylenes to ketones: a route to protected tertiary propargyl alcohols<sup>+</sup>

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The base-catalyzed addition of alkynylsilanes to ketone derivatives enables the formation of various silylprotected propargylic alcohols. Commercially available and inexpensive potassium bis(trimethylsilyl)amide (KHMDS) serves as an efficient transition metal-free catalyst and permits the functionalization of a variety of derivatives, including pharmaceuticals and biorelevant compounds. Overall, the presented system complements classical routes to protected tertiary propargylic alcohols that mainly rely on stoichiometric processes or fluoride-mediated reactions.

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#### Introduction

Propargyl alcohols are ubiquitous building blocks in chemical synthesis, being highly valued for their widespread application as valuable synthetic intermediates or medicinally relevant molecules themselves.<sup>1-15</sup> They participate in a diverse array of transformations, owing this to their multifunctionality, and thereby being the subject of numerous studies. Protected propargyl alcohols can be accessed via well-developed stoichiometric methods, including mainly the use of a combination of propargyl alcohol, chlorosilane and organolithium reagent (Fig. 1).<sup>16</sup> Such approaches are not without some disadvantages, including the need for an excess of both corrosive halosilane and hazardous n-butyllithium, little accessibility to commercial propargyl alcohol derivatives (compared with ubiquitous ketones), and the purification requiring high amounts of solvents (column chromatography). Moreover, the final isolating yields could be improved. For example, the reaction of 1-diphenyl-2-propyn-1-ol (Merck - 25 g per 139 €) gave the desired product in 81% yield, whereas our methodology using benzophenone as the starting reagent (Merck – 25 g per 11  $\in$ ) led to identical product 3t in 97% yield. Furthermore, an analogous stoichiometric reaction utilizing ketones requires a twostep pathway (the reaction with in situ generated (trimethylsilyl)acetylide followed by the subsequent O-silylation).<sup>17</sup> On the other hand, the concept of using silvlacetylenes and ketones as the substrates has also been studied in the presence

of fluorine reagents (*e.g.*, tetrabutylammonium fluoride – TBAF,<sup>18–20</sup> cesium fluoride – CsF,<sup>21</sup> *etc.*<sup>22,23</sup>). However, also these strategies have several drawbacks including lower selectivity and efficiency (formation of byproducts<sup>19,21,22</sup> and moderate yields<sup>19,21,24,25</sup>), the need for expensive crown ethers (CsF),<sup>21</sup> and narrow substrate scope.

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In this context, it is also worth noting the classical alkynylation of carbonyl compounds for the generation of unprotected propargylic alcohols, originally discovered by Alexei Favorskii in the early 1900s.<sup>26</sup> Here, besides stoichiometric approaches, several catalytic protocols were developed as well.<sup>27–37</sup>

The application of Earth-abundant species as catalysts have gained recent significant attention in organic chemistry.<sup>38-49</sup> Considering our recent success in activating organometalloids under sustainable catalysis,<sup>50–56</sup> we reasoned that an appropriate catalytic manifold could provide an efficient platform to generate diversified libraries of protected propargyl alcohols. To address the limitations of previously mentioned methods, herein we report the KHMDS-catalyzed addition of silylacetylenes to ketones. Examples of biorelevant molecules transformed to the corresponding protected alkynols include camphor (topical medication), (R)-(–)-carvone (food additive), nabumetone (nonsteroidal anti-inflammatory drug), *etc*. Thereby, the mentioned late-stage functionalization may lead to potentially biologically interesting compounds.

#### **Results and discussion**

In optimization studies, summarized in Table 1, we investigated the addition of bis(trimethylsilyl)acetylene to acetophenone.

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Fig. 1 Context of the investigation.

Table 1 Optimi	zation of addition	of silylacety	lene <b>2a</b> to	ketone 1a <sup>a</sup>
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$\begin{array}{c} O \\ Ph \\ \hline CH_3 + Me_3Si \\ \hline SiMe_3 \end{array} \xrightarrow{\text{KHMDS (3 mol%)}} \begin{array}{c} H_3C \\ Ph \\ \hline DME (1 mL), \end{array} \xrightarrow{\text{H}_3C} \begin{array}{c} O \\ Ph \\ \hline CH_3 \\ \hline CH_$				
<b>1a</b> (1	mmol) <b>2a</b> (3 mmol) <i>Ar</i> , 80°C, 2 h	3a Sinney		
Entry	Variation from standard conditions	Conversion of $1a^{a}$ [%]		
1	No change	99 (95)		
2	No catalyst	$0^c$		
3	Under solvent-free conditions	$58^b$		
4	1 mmol of <b>2a</b>	19		
5	2 mmol of 2a	90		
6	Trimethylsilylacetylene instead of 2a	$80^b$		
7	1.5 mol% of KHMDS	$60^b$		
8	3 mol% of KOH at 80 °C	$0^b$		
9	3 mol% of <i>t</i> -BuOK at 80 °C	$20^{b}$		
10	3 mol% of KF at 80 °C	$0^b$		

11 3 mol% of NaHMDS at 80 °C 0 12 In toluene  $30^{b}$ 13 In 1,4-dioxane

Phenylacetylene instead of 2a 14

<sup>a</sup> Conversion determined via GC, with n-dodecane as internal standard. Isolated yield in parenthesis. <sup>b</sup>After 2 h. <sup>c</sup>After 24 h. <sup>d</sup>Solvent-free cond.

 $0^b$ 

 $0^{c,d}$ 

After several attempts, the ideal reaction conditions were identified (Table 1, entry 1), giving product 3a in a 95% isolated yield. Control reactions revealed that the reaction does not proceed without the catalyst (entry 2). Instead, it was found that the reaction still works fine under solvent-free reaction conditions (entry 3). To ensure full conversion of 1a, it is needed to use an excess of 2a (entries 1, 5, and 6). What is more, such an excess of bis(trimethylsilyl)acetylene (BTMSA) excludes the formation of small amounts of diadduct. Please note, that 2a can be readily recovered. For details, please see Fig. 8 (part D). Next, the attempt to replace the silvlating source with trimethylsilylacetylene gave an inferior result (entry 7). Further experiments showed that other main-group mediators were mostly inactive under the tested conditions (entries 9-12). Considering the Favorskii reaction, we also checked simple phenylacetylene as the reaction partner with 1a in the presence of KHMDS. However, no product was observed after 2 and 24 h (entry 14).

Next, a variety of different ketones were tested to evaluate the generality and functional-group tolerance of our protocol (Fig. 2). A wide range of 1-substituted ethanones worked efficiently under the reaction conditions (3a-3i). As an initial example 3a, ketones bearing electron-donating alkyl groups were readily converted (3b-3c), as well as phenanthrene derivative 3e (70% yield). Gratifyingly, halogenated acetophenones were readily adopted in this protocol (3g-3j, 76-79% yield), however, they required a higher amount of the catalyst (6 mol%). Moreover, other useful derivatives were also well tolerated, and led to protected alkynols 3k-3m in good to excellent yields (79–99%). Notably, 5-hexen-2-one also participated effectively in this reaction (3n, 75% yield), while preserving the ene-functionality untouched. Encouraged by these results, we then investigated the use of heterocyclic ketones. All of them afforded the expected products in good yields (30-3p, 62-70%). Subsequently, we tested our methodology on variously substituted propyl ketones. Simple nonan-3-one, as well as propiophenone and its fluoro-substituted derivative reacted well, providing 3q, 3r, and 3s respectively in high yields (70-99%). Gratifyingly, two different benzophenones as well as cyclohexyl ketones were also readily adopted in this protocol (3t-3w, 94-99% yield). Finally, cyclohexanone was also well tolerated, and led to protected alkynol 3x in excellent yield (91%).

Having demonstrated the unique robustness and versatility of our strategy, we sought to explore the late-stage functionalization of biorelevant compounds including drugs. Pleasingly then, camphor, (R)-(-)-carvone, and nabumetone were isolated in good to excellent yield (4a-4c; 72-96%; Fig. 3). Intrigued by the high efficiency and selectivity of the transformation, we next pursued the development of further applications of our catalytic system. Encouragingly, this strategy can also be applied to silvlacetylenes other than bis(trimethylsilyl)acetylene (2a).

As shown in Fig. 4, the addition of 1-phenyl-2-trimethylsilylacetylene (2b), ((2-fluorophenyl)ethynyl)-trimethylsilane (2c), 2-((trimethylsilyl)ethynyl)pyridine (2d), and trimethyl (thiophen-3-ylethynyl)silane (2e) was performed, successfully



Fig. 2 Substrate scope for the addition of bis(trimethylsilyl)acetylene to ketones in the presence of KHMDS.





providing protected alkynols 5a-5j, in very good yields (up to 99%).

With these outcomes in mind, and given the similarity of aldehydes, we hypothesized that the presented addition reaction might allow convenient access to various protected secondary alkynols. In contrast to ketones, the reactions with the corresponding aldehydes were less selective and efficient, and somehow, this is in accordance with TBAF-mediated protocol (Fig. 5).<sup>19</sup>

For instance, the reaction of 3.0 eq. of 2a with 1.0 eq. of benzaldehyde led to the mixture of mono- and diadduct (4:3). Notably, in the case of more sterically hindered ketones, we observed only traces of the above-mentioned diadducts (<1%).



**Fig. 4** Substrate scope for the addition of different silylacetylenes to ketones in the presence of KHMDS.



Fig. 5 Initial reaction between aldehydes and BTMSA under standard conditions.

Their formation suggests that protected secondary alkynols can serve as competitive substrates toward bis(trimethylsilyl)acetylene. The same result was obtained for the reaction of 3.0 eq. of 2a with 1.0 eq. of 4-bromobenzaldehyde. Specifically, a mixture of mono- and diadduct was also observed (1:4). Considering this, we decided to check the influence of higher amounts of BTMSA.

Indeed, when 6.0 eq. of **2a** was used, we observed the corresponding products **7a** and **7b** exclusively. Unfortunately, the aldehydes with the electron-withdrawing group still gave the mixture of mono- and diadduct. What is more, picolinaldehyde, 4-nitrobenzaldehyde, and decanal were non-reactive. Next, we were wondering that reaction of benzaldehyde with 1-phenyl-2-trimethyl-silylacetylene (**2b**) should resolve the issue of selectivity. Surprisingly, we did not observe any conversion of benzaldehyde. The reason for the observed difference is not apparent at the moment. However, further investigations involving aldehydes and silylacetylenes are ongoing in our laboratory.

The key goals of this study were to simplify the synthesis and isolation of the protected tertiary alkynols, as well as show the scalability of the proposed methodology. Therefore, our protocol was successfully scaled up to a 10 mmol scale yielding 98% (2.84 g) of product **3a** (Fig. 6).

Once the scope of carbonyls was identified, our KHMDS-promoted addition was compared with other established methods leading to protected/unprotected tertiary alkynols (Fig. 7).



Fig. 6 Scaled up synthesis of 3a.



comparison of base-mediated reactions leading to tertiary alkynols

Fig. 7 Applications of varied addition methods leading to protected or unprotected alkynols.

Admittedly, all mentioned strategies are not without their own disadvantages. In the case of this protocol, the main drawback is the low reactivity of aldehydes, unlike ketones. But apart from that, several salient benefits of our strategy should be outlined. First of all, this is the first chemoselective method utilizing BTMSA as the substrate - leading exclusively to monoadduct products. There are two important facets. Firstly, bis (trimethylsilyl)acetylene is commercially available and inexpensive. Secondly, its use leads to O- and C-protected alkynols in a one-step procedure. Furthermore, the addition of BTMSA into carbonyls followed by selective deprotection can lead to terminal alkynols. Thus, being an indirect addition of acetylene. The other noteworthy feature of our strategy is the remarkable reactivity of ketones. It enabled the synthesis of a variety of protected tertiary alkynols including biorelevant compounds such as pharmaceuticals. Moreover, this protocol was scaled up to a 10 mmol scale. This once again makes it clear that the proposed methodology has significant application potential. Lastly, considering its operational simplicity, this reaction system provides a sustainable alternative to existing synthetic solutions. Notably, the exclusion of column chromatography leads to savings in many areas (*e.g.*, solvents, silica, time consumption, *etc.*).

In the end, we turned our attention to further applications of our methodology, as well as its sustainability and mechanistic insights (Fig. 8–10).

The KF/methanol system usually results in the deprotection of trimethylsilyl moiety, while the bulky triisopropylsilyl group remains untouched. By subjecting 2.5 mmol of potassium fluoride to the solution of 3a (Fig. 8A) or 5k (Fig. 8B) in methanol, the quantitative amounts of unprotected alkynol 8a and C-protected alkynol 8b were isolated. We could then successfully transform the silyl-protected alkynols into different products, thus showing the possibility to synthesize more complex products with challenging substitution patterns. Furthermore, the broader utility of our strategy is highlighted by the facile conversion of previously obtained O-silylated alkynol 5e to a highly important enyne derivative (Fig. 8C). To the best of our knowledge, this is the first example of direct elimination of -OTMS group from alkynols leading to enynes (please note that recently, Vasilyev reported on similar acidmediated elimination of TMS ethers of CF<sub>3</sub>-benzyl alcohols).<sup>57</sup> To date, unprotected alkynols were generally converted to enynes by using methanesulfonyl chloride/triethylamine system. Lastly, our initial idea was to deliver a sustainable synthetic protocol. Thus, an excess of silvlacetylene (mainly 2a)



Fig. 8 Potential pathways for derivatizations and rationale for the excess amount of silylacetylene.



Fig. 9 Illustrations of carbonyl band disappearance (top) recorded using realtime FT-IR spectroscopy during the addition of 2a to 1b at 80 °C.



Fig. 10 Plausible mechanism for KHMDS-catalyzed addition of silylacetylenes to carbonyls.

could be regarded as a significant drawback of our methodology. Fortunately, this issue should not be considered problematic because bis(trimethylsilyl)acetylene (as well as 1-phenyl-2-trimethylsilylacetylene) can be readily recovered at the isolation stage (Fig. 8D).

Next, to get some mechanistic insights into this base catalysis, we conducted preliminary experiments. For instance, the addition was performed in the presence of a typical radical scavenger such as TEMPO (100 mol%), giving the desired product (with almost the same efficiency), thereby implying that radical pathways were likely not operative. Moreover, we monitored the reaction system using real-time *in situ* FT-IR spectroscopy. The kinetic plots obtained for the addition of BTMSA (**2a**) to 2-methylacetophenone (**1b**) confirmed a rapid disappearance of the distinguishing band at 1689 cm<sup>-1</sup> of the carbonyl moiety (Fig. 9, top) with the simultaneously increased intensity of the Si–O band at 1115 cm<sup>-1</sup> (Fig. 9, bottom).

Previously, Scheidt presented very convincing evidence for hypervalent silicon intermediates resulting from the reversible addition of potassium ethoxide. Considering this, we performed <sup>29</sup>Si NMR analysis of the mixture containing stoichiometric amounts of BTMSA and KHMDS (ratio 1:1) in acetonitrile-d<sub>3</sub>. In this particular experiment, we still observe the signal corresponding to BTMSA (-19.2 ppm, lit. val. = -19.2 ppm in CDCl<sub>3</sub>). Moreover, two additional signals appeared at -17.3 ppm and 7.5 ppm. The former could be assigned to trimethylsilylacetylene. However, <sup>1</sup>H NMR analysis excluded such a situation (no signal for the acetylenic proton, lit. val. = 2.3 ppm (ref. 58)), suggesting more likely the presence of different, hypervalent silvlacetylene species. However, in the case of pentacoordinated silicon species it is not so clear. Especially, there is little knowledge concerning pentavalent trialkylsilyl species resulting from the reversible addition of disilazide anion. In general, all the previous protocols for the base-catalyzed addition of silylacetylenes to carbonyls were assuming the intermediacy of hypervalent silicon species. In our specific case, it is also the most probable pathway. Thus, a plausible catalytic cycle is presented in Fig. 10.

#### Conclusions

In conclusion, the base-catalyzed addition of silvlacetylenes to ketones has been enabled using commercially available reagents. The employment of inexpensive potassium bis(trimethylsilyl)amide as the catalyst and bis(trimethylsilyl)-acetylene not only provides a mild and economical alternative to canonical catalysis by fluoride anions, but also represents a highly chemoselective approach with an exceptional scope that is currently absent in other methods. Hence, late-stage derivatization of biorelevant compounds, as well as selective protodesilvlation and OTMS elimination, further demonstrated the synthetic potential of the transformation. The scalability and practicality of this reaction were also demonstrated by both gram-scale and recovery experiments. We expect that our strategy will streamline the synthesis of different organosilicons and enable the development of new synthetic pathways involving potassium bis(trimethylsilyl)amide and bis(trimethylsilyl)acetylene as the reagents.‡

## Conflicts of interest

There are no conflicts to declare.

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