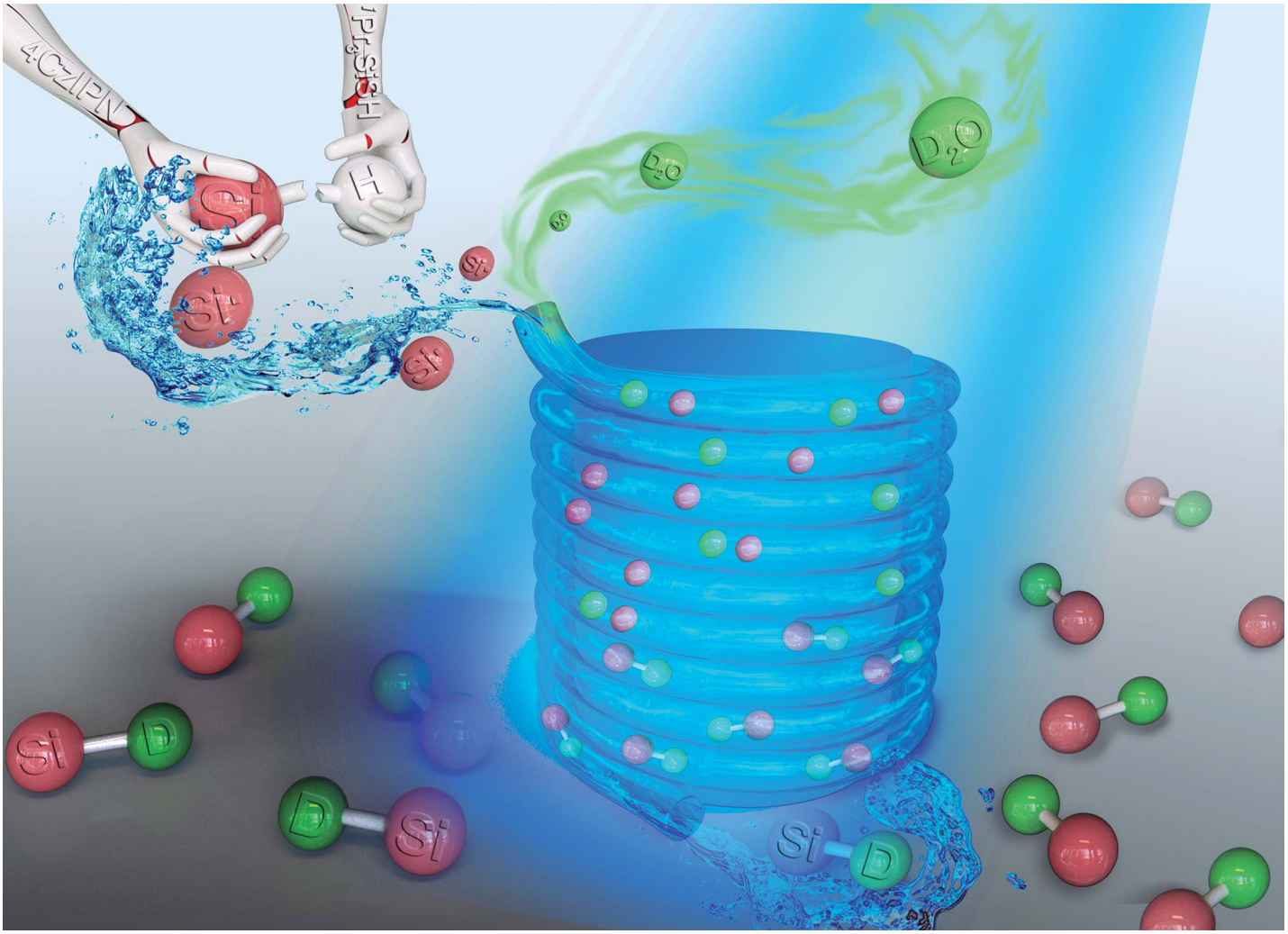

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Visible-light-mediated deuteration of silanes with deuterium oxide

An unprecedented visible-light-mediated deuteration of silanes using deuterium oxide has been developed in a metal-free fashion.

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Visible-light-mediated deuteration of silanes with deuterium oxide†

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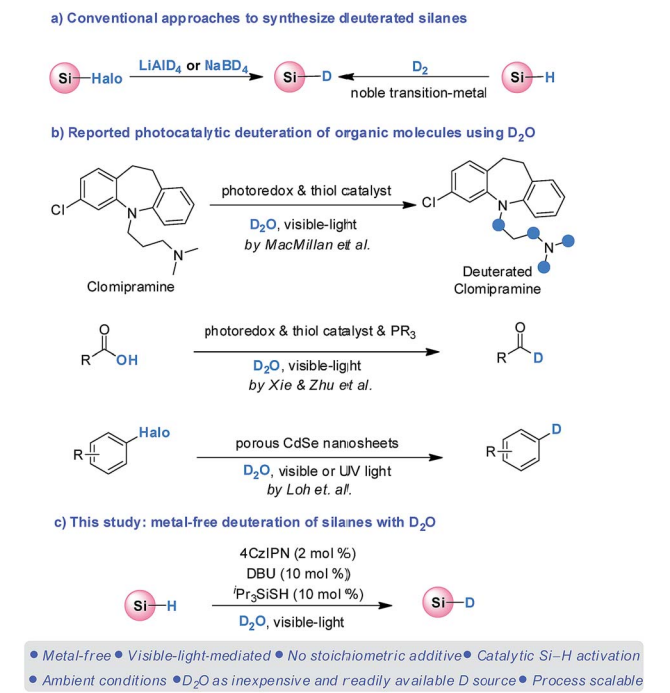
Isotopically labeled compounds are highly desirable as they can serve as both mechanistic probes in chemistry and diagnostic tools in medicinal research. Herein, we report an unprecedented visible-light-mediated metal-free deuteration of silanes using D_2O as an inexpensive, readily available, and easy to handle deuterium source. A broad range of aryl- and alkyl-substituted silanes were deuterated with high deuterium incorporations and yields. Furthermore, a 100 gram-scale synthesis was demonstrated using continuous-flow micro-tubing reactors, where enhanced reaction efficiency was obtained. The photoredox-catalyzed polarity matched hydrogen atom transfer (HAT) between silanes and the thiol HAT catalyst was responsible for the efficient deuteration.

Introduction

Deuterium-labeled compounds are of significant importance in organic synthesis,[1] mechanistic investigations,[2] mass spectrometric studies,[3] and pharmaceutical discoveries.[4] The increasing demand for deuterium-labeled compounds has recently stimulated the quest for convenient, selective, and especially catalytic approaches for their preparation.[5] A number of valuable methods have therefore been developed.[6] In this context, deuterated silanes not only serve as important probes for mechanistic studies in organic silicon chemistry, but are also versatile reagents for deuterium-labeling, which can add catalytically to C–X (X = C, N, O) multiple bonds through well-established hydrosilylations, as well as to reduce carbon–halogen and carbon–oxygen bonds.[7,8] Despite these advantages, there are only limited protocols available for preparation of deuterated silanes. Conventionally, deuterated silanes are prepared by either reduction of halosilanes with $LiAlD_4$ or $NaBD_4$ (ref. 9) or isotopic exchange of the Si–H/D bond of silanes with D_2 through noble transition-metal catalysis (Scheme 1a).[10] However, the use of stoichiometric amounts of expensive metallo-deuteride reagents and the requirement of equipment-demanding D_2 with noble metals undermine their wide application in synthetic chemistry. The development of a catalytic procedure using deuterium oxide (D_2O) as the deuterium source for silanes deuteration therefore represents an appealing strategy in term of mildness, sustainability, and cost, which by far has not been realized.



Scheme 1 Silane deuteration and photocatalytic deuteration using D_2O.

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† Electronic supplementary information (ESI) available: Experimental procedures, characterization data and NMR spectra of all new compounds. See DOI: 10.1039/c9sc02818h

‡ These authors contributed equally to this work.

Significant developments have been achieved for photocatalysis over the past decade, which enables previously inaccessible transformations.[11] In this context, photocatalytic deuteration of medicinally and synthetically valuable organic molecules using D_2O has recently received considerable attentions (Scheme 1b). For instance, the MacMillan group have recently pioneered a photoredox-mediated HAT process for selective deuteration of α-amino C(sp^3)–H bonds with D_2O, enabling a powerful protocol to incorporate deuterium in pharmaceutical compounds.[12] Very recently, the Xie and Zhu group realized an elegant deoxygenative deuteration of carboxylic acids with D_2O for the synthesis of deuterated aldehydes, through the synergistic combination of photoredox catalysis, thiol catalysis and phosphoranyl radical chemistry.[13] Both reactions relied on the HAT process between the carbon or acyl radical intermediates and the thiol catalyst which is in equilibrium with D_2O. In addition, the Loh group have reported a deuteration of halogenated compounds using D_2O catalyzed by porous CdSe nanosheets under visible or UV light irradiation through a photocatalytic D_2O splitting process.[14]

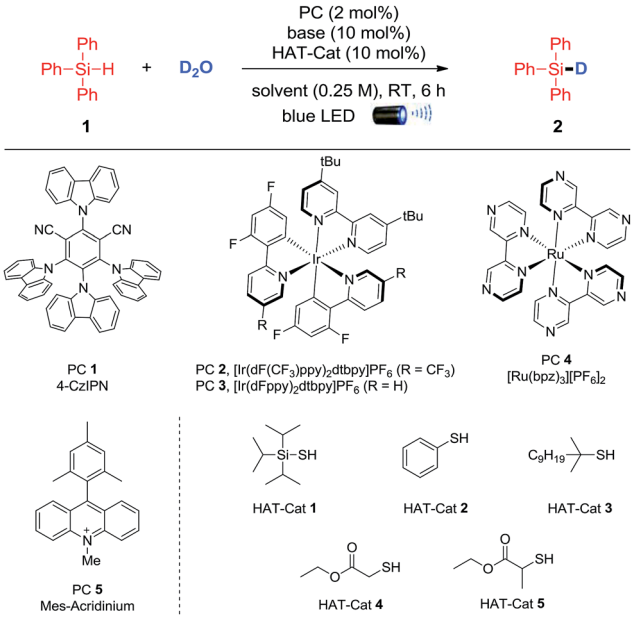
We have recently reported a visible-light-mediated metal-free hydrosilylation of alkenes *via* Si–H activation.[15] With the combination of an organo photocatalyst, 1,2,3,5-tetrakis(carbazol-9-yl)-4,6-dicyanobenzene (4CzIPN), and triisopropylsilanethiol HAT catalyst, the hydrosilylation of electron-rich alkenes proceeded smoothly. In the proposed mechanism, the polarity matched HAT process between the thiyl radical and silane facilitates the generation of a silyl radical, which subsequently adds to alkenes to achieve the hydrosilylation products. Taking the significance of deuterated silanes into consideration, we speculated that if D_2O is present instead of an alkene, the generation of deuterated thiol would occur reversibly,[12,13] which might subsequently result in the formation of a Si–D bond through a deuterium atom transfer (DAT) between the silyl radical and the deuterated thiol.[16] Herein, we report an unprecedented metal-free deuteration of silanes using D_2O as an easily handled, inexpensive, and readily available deuterium source (Scheme 1c).

Results and discussion

Optimization of reaction conditions

Our investigation of the proposed deuteration protocol was initiated by using triphenylsilane **1** as the model substrate. In the presence of photocatalyst 4CzIPN (PC **1**, 2 mol%), DIPEA (10 mol%), and triisopropylsilanethiol (HAT-Cat **1**, 10 mol%) in EtOAc, the deuteration of triphenylsilane **1** with D_2O under blue LED irradiation ($\lambda_{max} = 470$ nm) proceeded smoothly to give the product in 77% yield with 89% D-incorporation (Table 1, entry 1), demonstrating the viability of the hypothesis. A systematic survey on the reaction parameters including photocatalysts, solvents, bases and HAT catalysts was subsequently performed. Several common photocatalysts (PC **1**–PC **5**) were evaluated and 4CzIPN remained the most efficient with respect to both the yield and D-incorporation. Iridium(III) catalysts bearing similar redox potentials to 4CzIPN, such as $Ir[dF(CF_3)ppy]_2(dtbpy)PF_6$ (PC **2**) and $Ir(dFppy)_2(dtbpy)_3PF_6$ (PC **3**) gave comparable D-incorporation (entries 2 and 3). Other photocatalysts such as $Ru(bpz)_3[PF_6]_2$ (PC **4**) and 9-mesityl-10-methylacridinium perchlorate (PC **5**) were not suitable for this transformation (entries 4 and 5). Among the solvents screened, EtOAc was the optimal, achieving the highest efficiency and D-incorporation (entries 6–8). The use of EtOAc as solvent was also green and economical. The use of base as additive had a big influence on the reaction outcome. Both K_2CO_3 and DBU resulted in excellent D-incorporations (entries 9 and 10), while other common bases such as Et_3N and DMAP were less effective (entries 11 and 12). The deuteration could also occur in the absence of base,

Table 1 Survey of the model deuteration conditions[a]



Entry	PC	Base	HAT-Cat	Solvent	Yield[b] (%)	D-inc.[c] (%)
1	PC **1**	DIPEA	HAT-Cat **1**	EtOAc	77	89
2	PC **2**	DIPEA	HAT-Cat **1**	EtOAc	40	80
3	PC **3**	DIPEA	HAT-Cat **1**	EtOAc	48	70
4	PC **4**	DIPEA	HAT-Cat **1**	EtOAc	—	—[d]
5	PC **5**	DIPEA	HAT-Cat **1**	EtOAc	—	—[d]
6	PC **1**	DIPEA	HAT-Cat **1**	CH_2Cl_2	50	13
7	PC **1**	DIPEA	HAT-Cat **1**	THF	20	73
8	PC **1**	DIPEA	HAT-Cat **1**	CH_3CN	19	61
9	PC **1**	K_2CO_3	HAT-Cat **1**	EtOAc	71	94
10	PC **1**	DBU	HAT-Cat **1**	EtOAc	78	95
11	PC **1**	Et_3N	HAT-Cat **1**	EtOAc	48	86
12	PC **1**	DMAP	HAT-Cat **1**	EtOAc	81	34
13	PC **1**	—	HAT-Cat **1**	EtOAc	82	21
14	PC **1**	DBU	HAT-Cat **2**	EtOAc	70	52
15	PC **1**	DBU	HAT-Cat **3**	EtOAc	60	40
16	PC **1**	DBU	HAT-Cat **4**	EtOAc	42	84
17	PC **1**	DBU	HAT-Cat **5**	EtOAc	61	52
18	No PC or HAT-Cat or light				—	—[d]

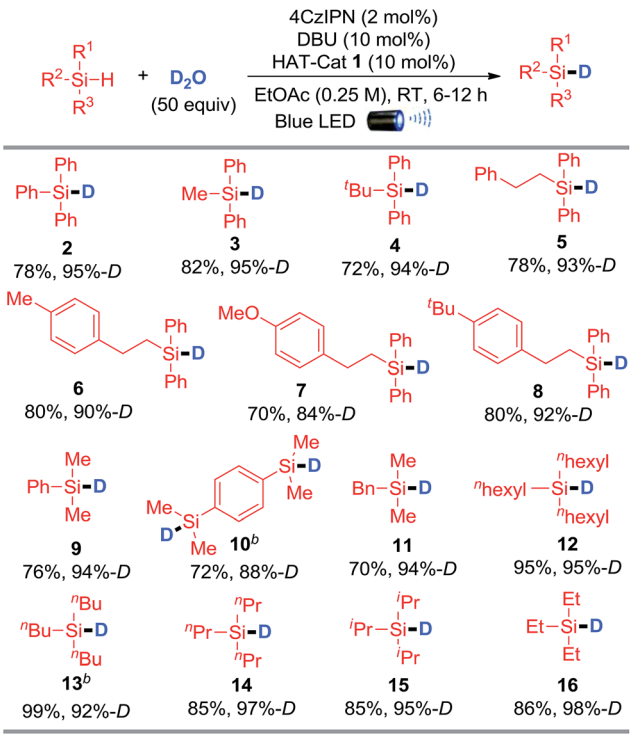
[a] Typical conditions: silane (0.5 mmol), D_2O (0.45 mL, 25 mmol), PC (0.01 mmol), base (0.05 mmol), and HAT-Cat (0.05 mmol) in solvent (2 mL), irradiated by 18 W blue LED. [b] Isolated yields of the Si–D/H mixtures. [c] Ratios determined by ^1H NMR spectroscopy. [d] Recovery of the starting silane.

albeit in much lower D-incorporation (entry 13). Thiol HAT catalysts with different S–H bond dissociation energy (BDE) were examined. Triisopropylsilanethiol (HAT-Cat **1**) was found to be the optimal HAT catalyst, whereas other catalysts such as PhSH (HAT-Cat **2**), *tert*-dodecanethiol (HAT-Cat **3**), ethyl 2-mercaptoacetate (HAT-Cat **4**), and ethyl 2-mercaptopropanoate (HAT-Cat **5**) gave moderate to good D-incorporations (entries 14–17). Finally, no deuterated silane **2** was generated in the absence of either the photocatalyst, the HAT catalyst, or light, demonstrating the necessity of all these components (entry 18).

Scope of the deuteration reactions

The generality of silane deuteration was evaluated employing the optimal reaction conditions (Table 1, entry 10). As depicted in Table 2, aryl-substituted silanes including tri-, di-, and mono-aryl silanes with different steric and electronic properties were well-tolerated to afford the corresponding deuterated products (**2–10**) in good to excellent D-incorporations. Disilanes such as *para*-phenylenebis(dimethylsilane) were also suitable substrates, smoothly delivering the product with two deuterium atoms incorporated (**10**). A series of trialkylsilanes with different sizes were effectively deuterated, affording the corresponding products with excellent D-incorporations (**11–16**). Notably, our protocol is efficient for the preparation of deuterated triethylsilane (**16**), a frequently utilized deuterated silane reagent in organic synthesis. It is worth mentioning that the labile benzylic C–H bonds were unperturbed during the deuteration event, highlighting the highly selective HAT for Si–H activation (**5–8, 11**). This visible-light-mediated metal-free protocol enables rapid and efficient deuteration of silanes using D_2O under mild conditions, which is distinguished from the existing methods that require the use of either expensive and operational cumbersome $LiAlD_4$ or equipment-demanding D_2 and noble transition-metals. It therefore represents a green and economic method for the preparation of deuterated silanes.

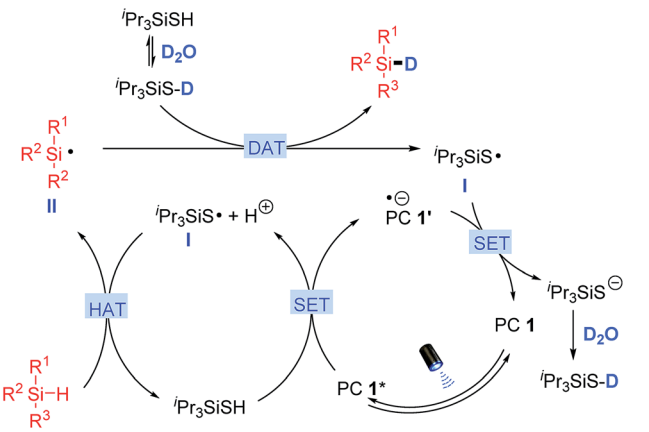
Table 2 Photo-mediated deuteration of silanes using D_2O[a]



[a] Typical conditions: silane (0.5 mmol), D_2O (0.45 mL, 25 mmol), DBU (7.5 μL, 0.05 mmol), triisopropylsilanethiol (10.7 μL, 0.05 mmol), and 4CzIPN (7.8 mg, 0.01 mmol) in ethyl acetate (2 mL), irradiated by 18 W blue LED. Isolated yields of the Si–D/H mixtures. Deuterium incorporation was determined by analysis of ^1H NMR spectra. [b] DIPEA (8.2 μL, 0.05 mmol) was used instead of DBU.

Mechanistic rationale

A proposed mechanism for silane deuteration is illustrated in Scheme 2 based on all experimental results. Initial photoexcitation of PC **1** (4CzIPN) generates its excited form PC **1***($E_{1/2}$ ($^*P/P^-$) = +1.35 V *vs.* SCE in MeCN),[17] which is reductively quenched by triisopropylsilanethiol ($E^{ox}_{1/2}$ = +0.28 V *vs.* SCE in MeCN) *via* a single electron transfer (SET) process to give the reduced PC **1′** and the thiyl radical **I** after deprotonation.[15] The presence of a catalytic amount of base presumably facilitates the deprotonation for the generation of thiyl radical **I**. The electrophilic thiyl radical then undergoes a polarity matched HAT to abstract a hydrogen atom from the hydridic Si–H bond of silane, generating the nucleophilic silyl radical **II**.[18] In the presence of excess amounts of D_2O, the H/D exchange of the thiol catalyst leads to dominant formation of the deuterated thiol (Fig. S7†).[12,13] The silyl radical **II** then abstracts a deuterium atom from the deuterated thiol to deliver the deuterated silane product and the thiyl radical **I**.[16] Single electron reduction of thiyl radical **I** ($E^{red}_{1/2}$ = −0.82 V *vs.* SCE in MeCN)[15] by PC **1′** ($E_{1/2}(P/P^-)$ = −1.21 V *vs.* SCE in MeCN)[17] regenerates the photocatalyst and the deuterated thiol after protonation with D_2O. No reaction occurred when radical scavenger TEMPO was added, supporting the above radical-based process. Furthermore, the light on/off experiments illustrated a total interruption of the reaction process in the absence of light and recuperation of reactivity on further illumination (Fig. S8†). This indicates that

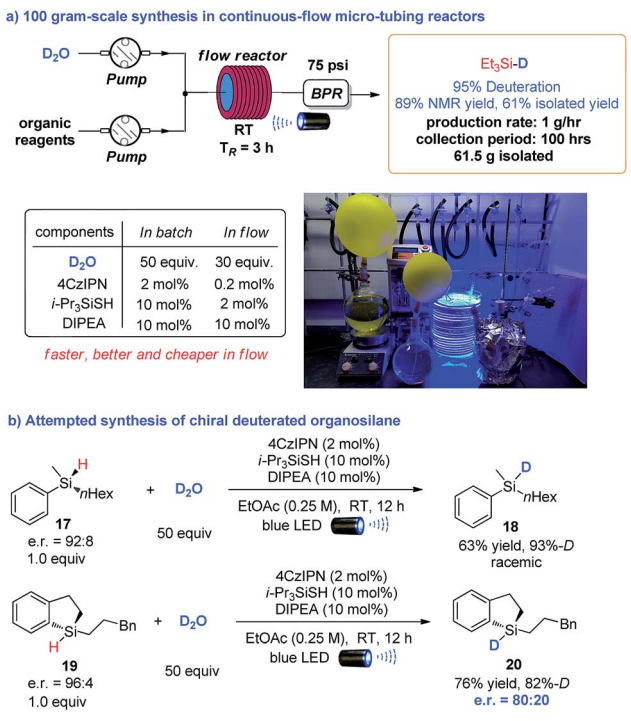


Scheme 2 Proposed mechanism for deuteration of organosilanes.

light was essential for this transformation, and any chain-propagation process should be short-lived.

Synthetic utilities of the deuteration methodology

To further demonstrate the synthetic utility of this methodology, we examined the feasibility of large-scale synthesis using continuous-flow micro-tubing reactors. As illustrated in Scheme 3a, the transformation was amenable to scale-up with 100 grams of starting triethylsilane assisted by an operationally simple continuous-flow setup, which resulted in the deuteration of triethylsilane with excellent D-incorporation (95%) and good crude yield (89% based on analysis of the crude ^{1}H NMR spectra). 61.5 grams of pure deuterated triethylsilane was isolated by a careful distillation of the crude product mixture, highlighting the potential for large scale synthesis. Notably, compared to the batch synthesis, the requirements of photocatalyst (4CzIPN), HAT catalyst (triisopropylsilanethiol) and D_2O to achieve an efficient transformation were all dramatically decreased in continuous-flow micro-tubing reactors, from 2 mol%, 10 mol% and 50 equivalents to 0.2 mol%, 2 mol% and 30 equivalents, respectively. The residence time was shortened to 3 h instead of the 12 h required in the batch reaction. This provides an even more economic pathway for the synthesis of deuterated silanes,[19] highlighting the superiority of micro-tubing flow reactors in photochemical synthesis.[20] Moreover, considering the pyramidal configuration of silyl radicals,[21] we envisioned that there might be an opportunity to access enantioenriched deuterated silanes starting from chiral organosilanes through memory of chirality.[22] Even though the acyclic chiral silane **17** afforded racemic product **18**, the chirality of cyclic chiral silane **19** was preserved in product **20** to a large extent *via* the photo deuteration protocol (Scheme 3b).[23]



Scheme 3 Reaction scaling up in continuous-flow reactors and synthesis of chiral deuterated silanes.

Conclusions

In summary, we have developed a convenient visible-light-mediated deuteration of silanes using D_2O by synergistic combination of an organophotocatalyst 4CzIPN and a thiol HAT catalyst in the presence of a catalytic amount of base additive. This protocol accommodates a wide range of silanes, achieving products with excellent D-incorporations, and is distinguished by its operational simplicity, metal-free character, mild reaction conditions, green solvent, and utilization of D_2O as an easily handled and inexpensive deuterium source. Furthermore, a scaling-up process of 100 grams of starting silanes has been demonstrated using an operationally simple continuous-flow setup, enabling an even more efficient and economic synthesis. We anticipate that this convenient and economic synthetic protocol to prepare deuterated silanes will promote the wide usage of these important reagents in both academic and industrial settings.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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