JOC *Note*

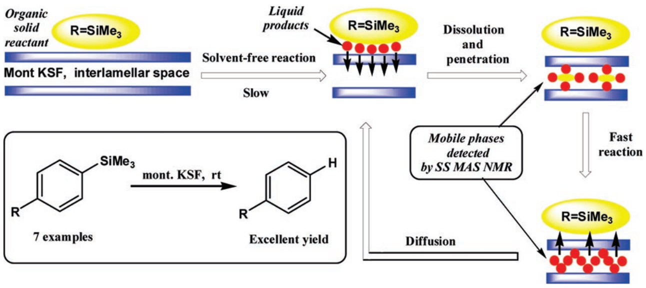
Efficient and Facile Ar−Si Bond Cleavage by Montmorillonite KSF: Synthetic and Mechanistic Aspects of Solvent-Free Protodesilylation Studied by Solution and Solid-State MAS NMR

Yossi Zafrani,* Eytan Gershonov, and Ishay Columbus

Department of Organic Chemistry, Israel Institute for Biological Research, Ness-Ziona 74100, Israel

yossiz@iibr.gov.il

Received April 1, 2007



A facile and efficient method for the cleavage of the Ar−Si bond of various aryl trimethyl silanes is described. When adsorbed on montmorillonite KSF (mont KSF), these arylsilanes readily undergo a solvent-free protodesilylation to the corresponding arenes at room temperature in excellent yields. This approach seems to be superior to the traditional mild methods (i.e., desilylation by TFA, TBAF, CsF), in terms of reaction yield, rate, and environmentally benign conditions. Some mechanistic studies using both solution and solid-state magic-angle spinning (SS MAS) ^{1}H NMR are also presented.

The use of clays as inorganic solid catalysts or as reaction media in various organic transformations has become widespread in the last two decades.[1−3] Such environmentally benign heterogeneous reactions often involve minimal waste, efficient catalyst recycling, increased yield and/or selectivity, and easier setup and workup procedures compared to conventional liquid-phase homogeneous reactions. In addition, mineral clays benefit from practical features such as stability, ease of handling, lack of corrosiveness, and low cost. For example, acid-treated montmorillonite (commercially known as mont KSF) shows high activity as solid support in many organic reactions. The catalytic activity is mainly attributed to the Brønsted acidic sites, generated by the interaction of water molecules with a metal ion in the interlamellar space.

Protodesilylation and electrophilic aromatic substitution of arylsilanes discovered a century ago have found extensive applications in organic synthesis since these reactions always occur at the *ipso* position.[4,5] In conventional applications, trialkylsilyl groups were used to block reactivity at specific sites or to direct *ipso* substitutions of arylsilanes for the regiospecific introduction of electrophilic functional groups.[6] A further creative application was discovered independently by Ellman[7] and Veber[8] in 1995, who developed a silicon-based traceless linker for solid-phase synthesis, utilizing the well-known protodesilylation of the Ar−Si bond.

The protodesilylation of some arylsilanes, in which the aryl moiety was functionalized with electron-donating groups, can be achieved in comparatively mild acidic conditions such as TFA,[9] boron trifluoride−acetic acid complex (2/3) and chloroacetic acid,[10] 1,1,1,3,3,3-hexafluoroisopropyl alcohol,[11] or in the presence of trimethylsilyl chloride and potassium iodide.[12] However, for most cleavages studied in the past, a strong acid was required (aqueous methanolic perchloric acid or sulfuric acid in acetic acid).[4,5] Since such harsh conditions may cause decomposition of the substrate or products, there is a considerable interest in developing milder and more environmentally benign methods for performing this process. For instance, recently, it has been published by Itami et al. that a C−Si (including Ar−Si) bond could be rapidly and efficiently cleaved by supercritical water.[13]

Herein we report the facile and efficient room temperature Ar−Si bond cleavage, using mont KSF clay as a solid support. The facility and efficiency of the process encouraged us to study the mechanism of this solvent-free protodesilylation (dry media), using both solution and solid-state magic-angle spinning (SS MAS) ^{1}H NMR techniques. A mechanistic study of such solvent-free reactions may provide valuable information on the nature of the active site within the inorganic matrix and on to the role the diffusion plays in their kinetics. These mechanistic insights may lead to improved synthetic tools useful for implementation in the so-called "green chemistry". Real time

---

(1) Varma, R. S. *Tetrahedron* **2002**, *58*, 1235.

(2) Balogh, M.; Laszlo, P. *Organic Chemistry Using Clays*; Springer: Berlin, 1993.

(3) Clark, J. H., Ed. *Catalysis of Organic Reaction by Supported Inorganic Reagents*; VCH: New York, 1994.

(4) Eaborn, C. *Pure Appl. Chem.* **1969**, 375.

(5) Chan, T. H.; Felming, I. *Synthesis* **1979**, 761.

(6) (a) Semmelhack, M. F.; Bisaha, J.; Czarney, M. *J. Am. Chem. Soc.* **1979**, *101*, 768. (b) Mills, R. J.; Taylor, N. J.; Snieckus, V. *J. Org. Chem.* **1989**, *54*, 4372. (c) Sengupta, S.; Snieckus, V. *Tetrahedron Lett.* **1990**, *31*, 4267. (d) Herrlich, M.; Hampel, N.; Mayr, H. *Org. Lett.* **2001**, *3*, 1629. (e) Zhao, Z.; Snieckus, V. *Org. Lett.* **2005**, *7*, 2523.

(7) (a) Plunkett, M. J.; Ellman, J. A. *J. Org. Chem.* **1995**, *60*, 6006−6007. (b) Woolard, F. X.; Paetsch, J.; Ellman, J. A. *J. Org. Chem.* **1997**, *62*, 6102.

(8) Chenera, B.; Finkelstein, J. A.; Veber, D. F. *J. Am. Chem. Soc.* **1995**, *117*, 11999.

(9) Diercks, R.; Vollhardt, K. P. C. *J. Am. Chem. Soc.* **1986**, *108*, 3150.

(10) Utimoto, K.; Otake, Y.; Yoshino, H.; Kuwahara, E.; Oshima, K.; Matsubara, S. *Bull. Chem. Soc. Jpn.* **2001**, *74*, 753.

(11) Lew, C. S. Q.; McClelland, R. A. *J. Am. Chem. Soc.* **1993**, *115*, 11516.

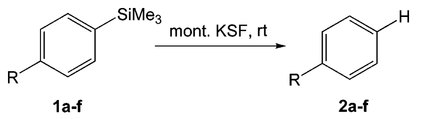
(12) Rander, F.; Wistrand, L. G. *Tetrahedron Lett.* **1995**, *36*, 5093.

(13) Itami, K.; Terakawa, K.; Yoshida, J.; Kajimoto, O. *J. Am. Chem. Soc.* **2003**, *125*, 6058.

(14) (a) O'Brien, P.; Williamson, C. J.; Groombridge, C. *J. Chem. Mater.* **1991**, *3*, 276. (b) Wagner, G. W.; MacIver, B. K.; Yang, Y. *Langmuir* **1995**, *11*, 1439. (c) Grey, C. P.; Corbin, D. R. *J. Phys. Chem.* **1995**, *99*, 16821. (d) Tao, T.; Maciel, G. E. *Environ. Sci. Technol.* **1998**, *32*, 350. (e) Pilkenton, S.; Hwang, S.-J.; Raftery, D. *J. Phys. Chem. B* **1999**, *103*, 11152 and references cited therein. (f) Wagner, G. W.; Bartram, P. W. *Langmuir* **1999**, *15*, 8113. (g) Wagner, G. W.; Koper, O. B.; Lucas, E.; Decker, S.; Klabunde, K. J. *J. Am. Chem. Soc.* **2001**, *123*, 1636 and references cited therein. (h) Dickinson, L. M.; Harris, R. K.; Shaw, J. A.; Chinn, M.; Norman, P. R. *Magn. Reson. Chem.* **2000**, *38*, 918. (i) Haouas, M.; Walspurger, S.; Taulelle, F.; Sommer, J. *J. Am. Chem. Soc.* **2004**, *126*, 599.

10.1021/jo0706170 CCC: $37.00

TABLE 1. Reactions of Arylsilanes 1a−f (1 mmol, ca. 10% w/w) with Mont KSF



run	compound	R	H_2O (equiv)	$t_{1/2}$ (h)	conv[b] (%)
1	**1a**	H	0	0.15 (0.16)[a]	100
2			1	0.6 (0.7)[a]	98
3			3	3	62
4			10	no reaction	0
5			D_2O (1−3)	not determined	100
6	**1b**	Me	1	<0.1 (<0.1)[a]	100
7	**1c**	*n*-butyl	1	1.6 (0.9)[a]	99[c]
8	**1d**	Br	1	85 (40)[a]	98[c]
9	**1e**	Cl	1	16.8	95
10	**1f**	F	1	2.4 (2.2)[a]	97

[a] The values in parenthesis were determined by SS MAS NMR. [b] Conversion (%) was determined by solution NMR. [c] Isolated yield for the nonvolatile products.

monitoring of the chemical and physical behavior of the reactants adsorbed on a solid support by SS MAS NMR has proved to be a powerful tool for mechanistic studies of solvent-free reactions.[14] However, despite the huge number of organic syntheses induced by inorganic solid supports, this technique is rarely used for mechanistic studies. In the present study, this technique was found to provide mechanistic insights not only for the solvent-free liquid−solid protodesilylations but also for a solid−solid type reaction (disilane **3** as an organic solid and mont KSF as an inorganic solid, vide infra). It will also be shown that in some cases the kinetic behavior of the reactions may be affected by the use of the SS NMR technique.

The reactivity of phenyltrimethyl silane (**1a**) (1.0 mmol, ca. 10% w/w) was examined toward mont KSF (dried by heating to 160 °C for 24 h), in the presence of different quantities of water (Table 1, runs 1−4). It was found that the rate of the protodesilylation of **1a** was slowed by an excess of water added to the mont KSF before mixing with the arylsilane (Table 1, runs 2−4), supposedly by blocking the acidic sites of the catalyst. We also found that silane **1a** underwent a facile and quantitative protodesilylation to benzene even with “dry” mont KSF (Table 1, run 1). However, the addition of 1 equiv of water is recommended for obtaining optimal reproducible results at ambient conditions.

Next, we have examined the reactivity of the other liquid arylsilanes, possessing electron-donating (**1b**,**c**), electron-withdrawing (**1d**−**f**), and bulky (**1c**) groups. The solid bis(trimethylsilyl)benzene (**3**) was also examined. These arylsilanes exhibit variability in their physical properties (e.g., viscosity, bp, etc.), and thus their protodesilylation may provide insights regarding the significance of the diffusion on the reaction kinetics. In addition, the use of this series of arylsilanes will also demonstrate the generality of this reaction. Arylsilanes **1b**,**c** were synthesized according to standard procedures.[13,15] It was found that the reaction of these compounds (**1b**−**f**) under similar conditions results in the formation of arene compounds **2b**−**f**, in a facile manner in a near quantitative yield (Table 1, runs 6−10).

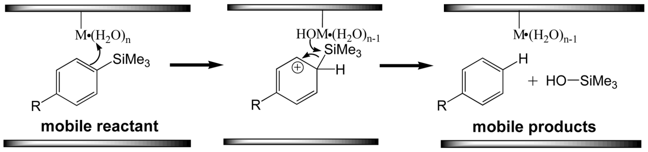


FIGURE 1. Proposed reaction mechanism for the protodesilylation of **1a**−**f** by mont KSF.

Inspection of the data presented in Table 1 reveals that the rate of the protodesilylation process depends on the nature of the arene functionality and thus accelerates when R is a small electron-donating group (as in **1b**) but slows when R is bulky (as in **1c**) or an electron-withdrawing group (as in **1d**−**f**). The protodesilylation profiles are compatible with a pseudo-first-order reaction, suggesting that the diffusion of the reactant toward the active sites is the rate-determining step (Figure S1). They are also compatible with the fact that the reaction is believed to proceed by the same mechanism as that of normal aromatic electrophilic substitution, involving a carbocation intermediate.[16] It is well-known that, in the standard protodesilylation, the formation of the carbocation intermediate is the rate-determining step, and the proton attack is at the silicon-bearing carbon, leading to a β-carbocation intermediate stabilized by the silyl group. However, in the aforementioned solvent-free protodesilylation, it seems that the diffusion of the reactants to the active sites of mont KSF plays a crucial role in the kinetics of the reaction. This can also be demonstrated by comparing the kinetics of **1c** (*p*-Bu, slower diffusion) and **1b** (*p*-Me) or **1d** (*p*-Br, slower diffusion) and **1e** (*p*-Cl) (Table 1, runs 7, 6, 8, and 9, respectively). While in the liquid media studied by Eaborn,[16] arylsilanes **1c**,**b** or **1d**,**e** react in closed protodesilylation rates, in our alternative solvent-free protodesilylation, the rates of **1c** and **1d** are considerably slower than those of **1b** and **1e**, respectively.

A plausible mechanism for the protodesilylation of arylsilanes **1a**−**f** by mont KSF is shown in Figure 1. The arylsilane is mainly protonated by a water molecule[17] within the hydrated interlamellar space, followed by an Ar−Si bond cleavage by a hydroxide ion attack at the silicon atom. SS MAS NMR spectroscopy is commonly used to observe the mobile phases within the solid support. The fact that both arenes **2a**−**f** and trimethyl silanol products were detected by the SS MAS ^1H NMR supports the suggested mechanism. Further mechanistic evidence supporting the involvement of bound water molecules within the hydrated interlamellar space was provided by the reaction of **1a** with “dry” mont KSF in the presence of D_2O in various quantities (Table 1, run 5). This reaction, which did not differ kinetically from the reaction involving H_2O, has led to benzene (and trimethyl silanol) but not to the corresponding deuterated benzene product. This was demonstrated by spiking of the product mixture with commercial benzene-d_1.

---

(15) West, R.; Jones, P. C. *J. Am. Chem. Soc.* **1968**, *90*, 2656.

(16) Eaborn, C. *J. Chem. Soc.* **1956**, 4858.

(17) Mont KSF (Aldrich) is a natural clay treated with sulfuric acid, leaving an acidic residue of ca. 5% in the clay. We cannot exclude the possibility that the protonation may partially occur by this mineral acid. However, following the well-established mechanism (together with our observations), it seems likely that arylsilanes are mainly protonated by bound water molecules within the hydrated interlamellar space (“M-H_2O”). For specific examples of similar mechanisms, see: (a) Arienti, A.; Bigi, F.; Maggi, R.; Marzi, E.; Moggi, P.; Rastelli, M.; Sartory, G.; Tarantola, F. *Tetrahedron* **1997**, *53*, 3795. (b) Bigi, F.; Chenisi, L.; Maggi, R.; Sartori, G. *J. Org. Chem.* **1999**, *64*, 1033. (c) Soriente, A.; Arienzo, R.; De Rosa, M.; Palombi, L.; Spinella, A.; Scettri, A. *Green Chem.* **1999**, 157. (d) Choudary, B. M.; Chowdari, N. S.; Kantam, M. L. *Tetrahedron* **2000**, *56*, 7291. (e) Bolognini, M.; Cavani, F.; Cimini, M.; Dal, Pozzo, L.; Maselli, L.; Venerito, D.; Pizzoli, F.; Veronesi, G. *C. R. Chimie* **2004**, *7*, 143.

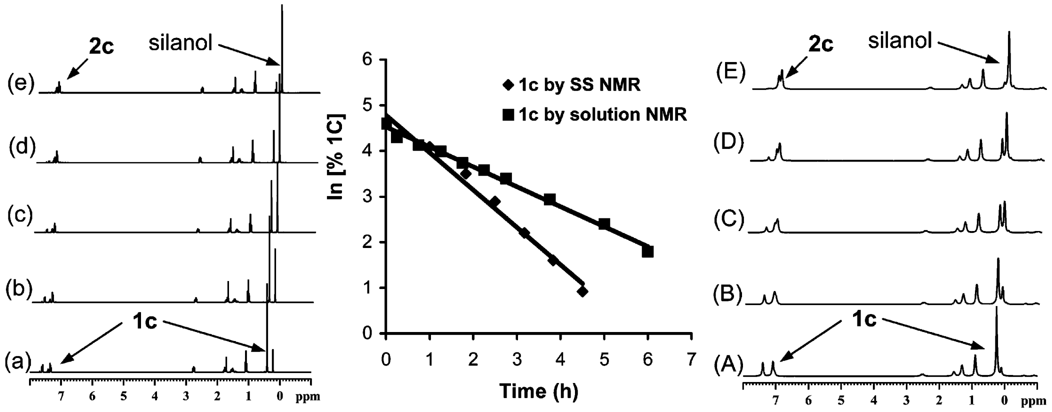
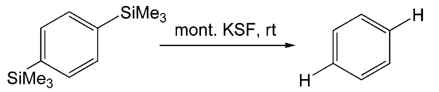


FIGURE 2. Left: ^{1}H solution NMR spectra obtained for arylsilane **1c** added to mont KSF at (a) 0.25 h, (b) 1.25 h, (c) 2.25 h, (d) 3.75 h, and (e) 6 h. Middle: reaction profile for arylsilane **1c** on mont KSF. Right: ^{1}H SS MAS NMR spectra obtained for solid arylsilane **1c** added to mont KSF at (A) 0.33 h, (B) 1.83 h, (C) 2.5 h, (D) 3.17 h, and (E) 4.5 h.

TABLE 2. Reaction of the Solid Disilane 3 with Mont KSF



3 **2a**

run	H_2O^a (equiv)	C_6D_6 (equiv)	*t* (h)	conversion[b] (%)
1	1	0	7	100
2	2	0	12	100
3	1	2	0.5	100

[a] Water was simply mixed and crushed with "dry" mont KSF. [b] Conversion (%) was determined by solution ^{1}H NMR.

Surprisingly, in the protodesilylation cases of **1c** and **1d**, the rates of the reactions measured by SS MAS ^{1}H NMR were found to be higher compared to those measured by solution ^{1}H NMR of the same reaction mixture (Table 1, runs 7 and 8). This effect is clearly illustrated in Figure 2 for the protodesilylation of **1c**. We assume that the protodesilylation of **1c**,**d**, in which the diffusion plays a significant role in the kinetic reactions, may be affected by the high spinning rate of the sample (ca. 8000 Hz). This in turn causes an acceleration of the reaction rate, supposedly by a centrifugation effect that improves the diffusion of these reactants. To the best of our knowledge, only one example demonstrating a centrifugation effect by the rate of MAS has been reported, where the adsorption properties of water on activated carbon were studied by Harris et al.[14h]

Prompted by these results, we proceeded to investigate the behavior of the solid bis(trimethylsilyl) benzene (**3**) under the same conditions as mentioned above, namely, simply mixing and crushing the solid organic compound with the solid inorganic mineral mont KSF. A quantitative double protodesilylation of the disilane **3** occurred, yielding the benzene product (Table 2). The chemistry of solid−solid reactions is well-documented and reviewed, and the chemist's interest in this type of reaction is permanently growing.[18,19] An organic reactionbetween two macroscopic solid materials is a difficult concept to conceive. Recently, it was shown by Scott and coworkers that in most cases grinding the two solid reactants together results in the formation of a liquid phase, and actually the reactions do not proceed in the solid phase.[20]

As in the case of liquids **1a**−**f**, the rate of the protodesilylation of **3** was slowed by an excess of water (Table 2, run 2). Interestingly, the kinetic behavior of this solid−solid type reaction was found to be quite different compared to its liquid−solid counterparts (liquids **1a**−**f** with solid mont KSF). Whereas the liquid−solid reaction exhibited an exponential kinetic profile, the solid−solid type reaction behaved as an autocatalytic process. The rate of the latter was dramatically enhanced along with the formation of the liquid products **1a** (intermediate that eventually protodesilylated to **2a**), **2a**, and trimethyl silanol, as shown in Figure 3. Figure 3 (left, a−e) shows that only a trace of benzene (ca. 7%) and silanol products appear after a 4 h reaction (supposedly by weak Brønsted acidity at low concentration that stems from the terminal hydroxyl groups located at the layer surface).[1] However, at this point, the reaction rate became faster, displaying autocatalytic features, as can also be seen in Figure 3 (middle). When this reaction was monitored by SS MAS ^{1}H NMR, no signal appeared at the beginning of the reaction, due to the solid state of reactant **3** (Figure 3, right, spectrum A). However, after 2.6 h, the mobile products benzene and trimethyl silanol appeared together with some soluble disilane **3**, and at this point, the reaction became faster, as mentioned above (Figure 3, right, spectrum B). We assume that the formation of the liquid products enhances the rate of the reactant diffusion (rate-determining step) into the interlayer sites (strong Brønsted acidity at high concentration stems from the hydrated interlayer metal cations),[1,17] by dissolving solid **3**. Furthermore, when an external source of benzene-d_6 was added (2 equiv) to the reaction mixture of disilane **3** and mont KSF, the solid reactant was fully converted to the benzene product after ca. 30 min (Table 2, run 3), indicating that dissolution of **3** has a primary importance on the reaction kinetic. One should add that, in all the experiments of solid disilane **3** performed, the monosilane intermediate **1a** appeared at 7.55 and 7.35 ppm, with an estimated concentration of <10% (the signals of **1a** overlap with signals of disilane **3** and the benzene product).

In order to highlight the synthetic utility of the mont KSF promoted protodesilylation, we compared it with some traditional mild methods, including the use of TFA,[9] TBAF,[6c] and CsF[6e] as desilylating reagents. Thus, we tested the reactivity of the higher (**1b**) and the lower (**1d**) reactive arylsilanes toward various conditions, as outlined in Table 3. In the case of **1b**,

---

(18) Tanaka, K.; Toda, F. *Chem. Rev.* **2000**, *100*, 1025.
(19) Nassimbeni, L. R. *Acc. Chem. Res.* **2003**, *36*, 631.
(20) Rothenberg, G.; Downie, A. P.; Raston, C. L.; Scott, J. L. *J. Am. Chem. Soc.* **2001**, *123*, 8701.

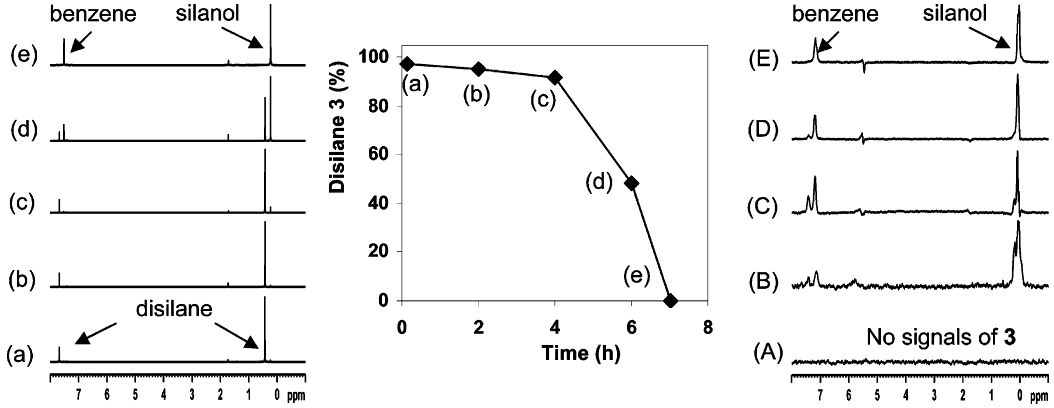


FIGURE 3. Left: ^{1}H solution NMR spectra obtained for solid disilane **3** added to mont KSF at (a) 0.15 h, (b) 2 h, (c) 4 h, (d) 6 h, and (e) 7 h. Middle: reaction profile for solid disilane **3** on mont KSF monitored by ^{1}H solution NMR. Right: ^{1}H MAS NMR spectra obtained for solid disilane **3** added to mont KSF at (A) 0.15 h, (B) 2.6 h, (C) 3.5 h, (D) 4 h, and (E) 5.5 h.

TABLE 3. Protodesilylation of Arylsilanes 1b,d under Various Conditions

		Desilylation Conditions				
run	silane	desilylation reagent	solvent	temp (°C)	time (h)	conv[a] (%)
1	**1b**	mont KSF	none	rt	0.5	99
2		TBAF (2 equiv)	DMF	rt	48	traces
3		TBAF (2 equiv)	DMF	60	18	86
4		TFA (1 equiv)	$CDCl_3$	rt	26	84
5		TFA (2 equiv)	$CDCl_3$	rt	5	95
6		CsF (2 equiv.)	DMF	60	48	traces
7	**1d**	mont KSF	None	rt	425	98
8		mont KSF	None	60	3	99
9		TBAF (2 equiv)	DMF	60	0.5	99
10		TFA (2 equiv)	$CDCl_3$	rt	48	traces
11		TFA (2 equiv)	$CDCl_3$	60	18	42
12		CsF (2 equiv.)	DMF	60	168	55

[a] Conversion (%) was determined by ^{1}H NMR.

the protodesilylation proceeded smoothly under acidic conditions such as mont KSF or TFA (Table 3, runs 1, 4, and 5). However, the reactivity of this electron-rich arylsilane (**1b**) toward mont KSF is 10 times greater than its reactivity toward TFA and considerably larger than that of the well-known fluoride-promoted desilylating agents TBAF and CsF. On the other hand, the electron-poor arylsilane **1d** was found to be reactive with both the fluoride reagent TBAF and mont KSF at 60 °C but was less reactive under TFA conditions (Table 3, runs 7−12). The acidic nature of mont KSF as well as other protodesilylating agents may affect acid-sensitive functional groups present on the molecule. However, the extremely facile and efficient protodesilylation promoted by mont KSF under mild conditions may enable the conduction of this reaction with a chemoselectivity toward such functional groups.

In summary, we described here a facile and efficient method for the cleavage of the Ar−Si bond of arylsilanes **1a**−**f** and **3** using mont KSF clay as an inorganic solid support. These arylsilanes readily undergo protodesilylation to the corresponding arenes at room temperature and in nearly quantitative yields. The kinetic studies using solution and SS MAS ^{1}H NMR revealed that the reaction is catalyzed mainly by water within the hydrated interlamellar sites, and the rate of the reaction is strongly dependent on the diffusion capability of the reaction components. This solvent-free approach seems to be superior not only by means of synthetic aspects but also in terms of green and inexpensive chemistry, compared to the traditional methods that are using desilylating agents such as TFA, TBAF, and CsF. In addition, we have investigated a solid−solid type reaction of arylsilane **3** (organic solid) and mont KSF (inorganic solid) using SS MAS ^{1}H NMR. It was found that this reaction behaves as an autocatalytic process, in which the mobile intermediate **1a** and products **2a** and trimethyl silanol cause an enhancement of the reaction rate by dissolving and dispersing the solid arylsilane **3** within the mont KSF medium.

Experimental Section

General Procedure. Mont KSF was dried by heating to 160 °C for 24 h, before it was mixed with measured quantities of water and arylsilanes **1a**−**f** (1 mmol, ca. 10 wt %) and crushed for 5 min (using a glass rod) at room temperature. For SS MAS ^{1}H NMR experiments, a sample of ca. 40 mg from the reaction mixture was inserted into a ZrO_2 rotor equipped with a Kel-F spherical insert. Spinning speed of 8000 Hz was used. For the solution ^{1}H NMR monitoring, aliquots of ca. 100 mg from the same reaction mixture were extracted with 0.75 mL of $CDCl_3$ at the appropriate time intervals. Isolated yield of the high boiling point products **2c**,**d** was calculated after extraction with ether (which does not extract the trimethyl silanol side product), filtration of the inorganic solid, and evaporation of the solvent.

In the solution NMR kinetic experiments for protodesilylation of arylsilane **3**, the reaction mixture was distributed into 10 sealed vials (200 mg in each), and at the appropriate time points, the reaction was quenched by adding 0.75 mL of $CDCl_3$, which also extracted the products (benzene at 7.36 ppm and trimethyl silanol at 0.06 ppm).

General Procedure for the Reactions of 1b,d with Desilylation Reagents in Solution. To a solution of the arylsilane (**1b**,**d**) (1 mmol) in 1.8 mL of the appropriate deuterated solvent was added 2.0 equiv of desilylation reagent (i.e., TBAF, TFA, CsF), and the reaction was monitored by solution ^{1}H NMR according to the data presented in Table 2.

Supporting Information Available: Figure S1, ^{1}H and ^{13}C NMR spectra of isolated products **2c**,**d**, ^{1}H NMR spectra of products **2a**,**b**,**e**,**f** at the end of the reaction. This material is available free of charge via the Internet at http://pubs.acs.org.

JO0706170