A Novel Silicon-Based Linkage and Cleavage Strategy for Solid-Phase Synthesis: Formation of Resin-Linked Zwitterionic Pentacoordinate Silicates as the Key Step and Release of the Target Molecules in a Traceless Fashion†

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A novel silicon-based linkage and cleavage strategy for solid-phase synthesis of aromatic organic compounds has been developed. The method is based on the following steps: (i) attachment of silanes of the formula type $R^1R^2(R^3O)Si(CH_2)_n\overline{NCH_2CH_2N(R^4)CH_2CH_2}$ (R^1 = aryl; R^2 = aryl, alkyl; R^3, R^4 = alkyl; n = 1, 3) to a Merrifield resin via R^4, (ii) reactions with the resin-linked silanes (chemical transformations of the aryl group R^1; $R^1 \rightarrow \rightarrow \rightarrow R^{1*}$), and (iii) treatment of the $R^{1*}R^2(R^3O)Si(CH_2)_n\overline{NCH_2CH_2N(R^4)CH_2CH_2}$-containing resin with 1,2-dihydroxybenzene in acetonitrile at 50 °C to give the cleavage products $R^{1*}H$ (release of the target molecules in a traceless fashion), R^2H, and R^3OH, along with the resin-linked zwitterionic pentacoordinate silicate of the formula type $(1,2\text{-}C_6H_4O_2)_2Si(CH_2)_n\overline{N(H)CH_2\text{-}CH_2N(R^4)CH_2CH_2}$.

Introduction

Combinatorial chemistry is a rapidly expanding area, the multistep synthesis of large combinatorial libraries of small organic molecules being one of the major aspects of this discipline.[1−8] The most significant work in this area has been performed using solid-phase strategies. Most of the current effort in solid-phase organic synthesis is being focused on the development of new linkage strategies.[9] The linker moiety, which connects the molecule being synthesized with the polymeric support material, plays a crucial role in any solid-phase synthesis strategy. Ideally, the linker should be stable to all chemical reactions used in a given synthesis sequence and should be cleaved quantitatively under conditions that do not degrade the desired target molecules. The design of so-called "traceless linkers" is of particular interest: upon cleavage from these linkers, products are formed that show no "trace" or "memory" of attachment to the solid support; i.e., new C−H or C−C bonds are formed at the linkage site of the cleaved molecules. By far the most examples of traceless linkers reported in the literature are silicon-based (for selected examples of silicon-based linkers, see refs 10−22).

In context with our studies on zwitterionic λ^5Si-silicates (for a recent review, see ref 23) we have

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(1) Gordon, E. M.; Barrett, R. W.; Dower, W. J.; Fodor, S. P. A.; Gallop, M. A. *J. Med. Chem.* **1994**, *37*, 1385−1401.
(2) Terrett, N. K.; Gardner, M.; Gordon, D. W.; Kobylecki, R. J.; Steele, J. *Tetrahedron* **1995**, *51*, 8135−8173.
(3) Früchtel, J. S.; Jung, G. *Angew. Chem.* **1996**, *108*, 19−46; *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 17−42.
(4) Balkenhohl, F.; von dem Bussche−Hünnefeld, C.; Lansky, A.; Zechel, C. *Angew. Chem.* **1996**, *108*, 2436−2487; *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 2288−2337.
(5) Hermkens, P. H. H.; Ottenheijm, H. C. J.; Rees, D. *Tetrahedron* **1996**, *52*, 4527−4554.
(6) Hermkens, P. H. H.; Ottenheijm, H. C. J.; Rees, D. C. *Tetrahedron* **1997**, *53*, 5643−5678.
(7) Booth, S.; Hermkens, P. H. H.; Ottenheijm, H. C. J.; Rees, D. C. *Tetrahedron* **1998**, *54*, 15385−15443.
(8) *Combinatorial Chemistry: Synthesis, Analysis, Screening*; Jung, G., Ed.; Wiley-VCH: Weinheim, Germany, 1999.
(9) James, I. W. *Tetrahedron* **1999**, *55*, 4855−4946.
(10) Plunkett, M. J.; Ellman, J. A. *J. Org. Chem.* **1995**, *60*, 6006−6007.
(11) Chenera, B.; Finkelstein, J. A.; Veber, D. F. *J. Am. Chem. Soc.* **1995**, *117*, 11999−12000.
(12) Boehm, T. L.; Showalter, H. D. H. *J. Org. Chem.* **1996**, *61*, 6498−6499.
(13) Han, Y.; Walker, S. D.; Young, R. N. *Tetrahedron Lett.* **1996**, *37*, 2703−2706.
(14) Plunkett, M. J.; Ellman, J. A. *J. Org. Chem.* **1997**, *62*, 2885−2893.
(15) Woolard, F. X.; Paetsch, J.; Ellman, J. A. *J. Org. Chem.* **1997**, *62*, 6102−6103.
(16) Stranix, B. R.; Liu, H. Q.; Darling, G. D. *J. Org. Chem.* **1997**, *62*, 6183−6186.
(17) Newlander, K. A.; Chenera, B.; Veber, D. F.; Yim, N. C. F.; Moore, M. L. *J. Org. Chem.* **1997**, *62*, 6726−6732.
(18) Hu, Y.; Porco, J. A., Jr.; Labadie, J. W.; Gooding, O. W.; Trost, B. M. *J. Org. Chem.* **1998**, *63*, 4518−4521.
(19) Hone, N. D.; Davies, S. G.; Devereux, N. J.; Taylor, S. L.; Baxter, A. D. *Tetrahedron Lett.* **1998**, *39*, 897−900.
(20) Curtet, S.; Langlois, M. *Tetrahedron Lett.* **1999**, *40*, 8563−8566.
(21) Briehn, C. A.; Kirschbaum, T.; Bäuerle, P. *J. Org. Chem.* **2000**, *65*, 352−359.
(22) Harikrishnan, L. S.; Showalter, H. D. H. *Tetrahedron* **2000**, *56*, 515−519.
(23) Tacke, R.; Pülm, M.; Wagner, B. *Adv. Organomet. Chem.* **1999**, *44*, 221−273.

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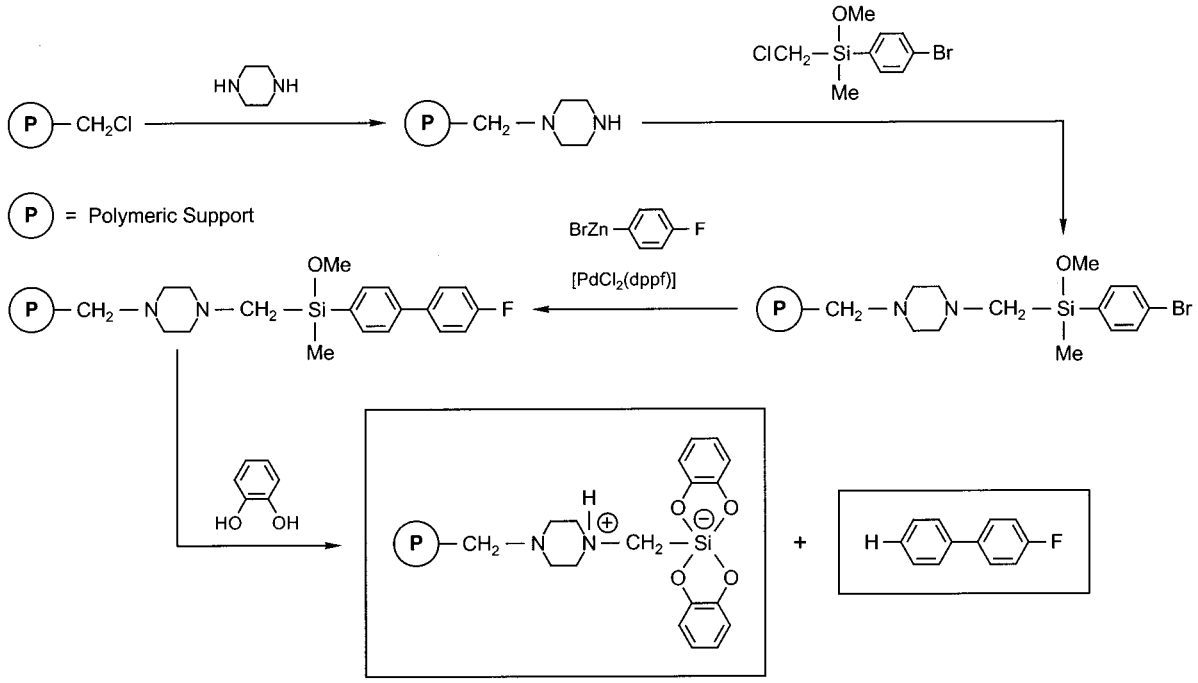
Scheme 1



demonstrated that silanes of the formula types $R(RO)_2Si(CH_2)_nNR_2$ and $R_2(RO)Si(CH_2)_nNR_2$ (R = organyl) undergo Si−C cleavage reactions with a variety of *vic*-diols, such as 1,2-dihydroxybenzene and glycolic acid derivatives.[23−33] These reactions proceed in organic solvents under mild conditions (room temperature) with high regioselectivity (selective Si−R cleavage; for related Si−C cleavage reactions, see refs 34−38). We have now succeeded in applying such reactions to a novel silicon-based linkage and cleavage strategy for solid-phase synthesis of aromatic organic compounds. As shown for a selected example in Scheme 1, the key step of this approach is a 2-fold Si−C cleavage with a *vic*-diol resulting (i) in the release of the target molecule in a traceless fashion and resulting (ii) in the formation of a zwitterionic pentacoordinate silicate linked to the polymeric support. We report here on the development and application of this novel silicon-based linkage and cleavage technique for solid-phase synthesis, including solution-phase model studies.

Results and Discussion

Syntheses of the Silanes Used as Precursors and Model Compounds. For the studies described in the sections Solution-Phase Model Studies and Solid-Phase Syntheses, a series of silanes (compounds **5**, **6**, **14**, **15**, **18**, and **19**; Schemes 2−5) were synthesized which were used as precursors or model compounds.

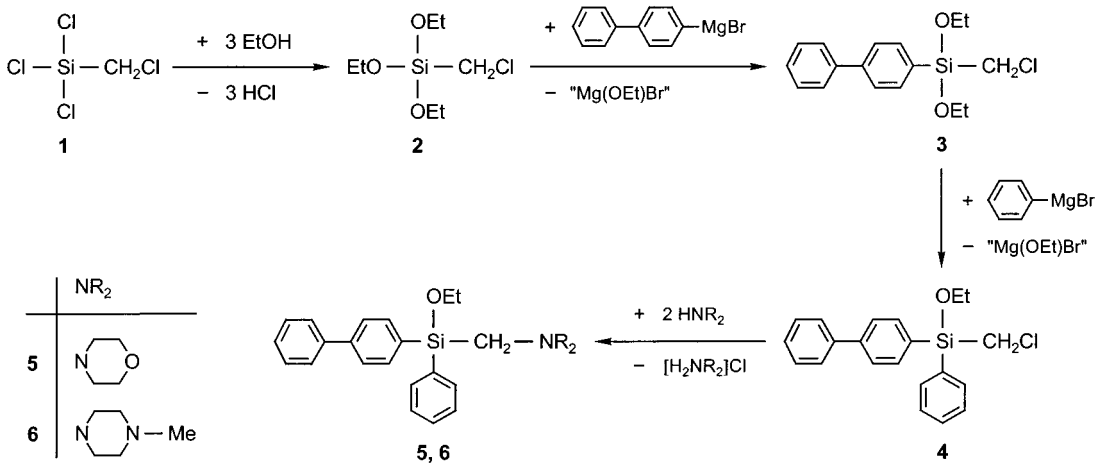
The (aminomethyl)(biphenyl-4-yl)ethoxyphenylsilanes **5** and **6** were synthesized according to Scheme 2 by four-step syntheses starting from trichloro(chloromethyl)-silane (**1**). Ethanolysis of **1** gave the triethoxysilane **2** (yield 80%), which upon treatment with (biphenyl-4-yl)-magnesium bromide gave the (biphenyl-4-yl)silane **3** (yield 65%). Subsequent reaction of **3** with phenylmagnesium bromide gave the phenylsilane **4** (yield 69%), which upon treatment with morpholine yielded the (morpholinomethyl)silane **5** (yield 54%). Reaction of **4** with 1-methylpiperazine gave the [(4-methylpiperazin-1-yl)methyl]silane **6** (yield 91%).

As outlined in Scheme 3, the silane **5** was alternatively prepared by treatment of **3** with morpholine (to give (morpholinomethyl)silane **7**, yield 76%), followed by reaction with phenylmagnesium bromide (to give phenylsilane **5**, yield 51%).

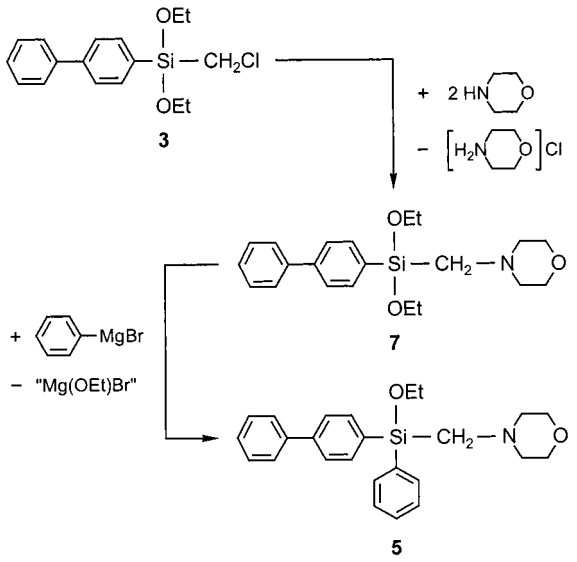
The (4-bromophenyl)methoxy(morpholinoalkyl)phenyl-silanes **14** and **15** were synthesized according to Scheme 4 by three-step syntheses starting from the respective (chloroalkyl)trimethoxysilanes **8** and **9**. In the first step, the 4-bromophenyl substituent was introduced by treatment with (4-bromophenyl)magnesium bromide (to give (4-bromophenyl)silanes **10** (yield 46%) and **11** (yield

(24) Strohmann, C.; Tacke, R.; Mattern, G.; Kuhs, W. F. *J. Organomet. Chem.* **1991**, *403*, 63−71.
(25) Tacke, R.; Sperlich, J.; Strohmann, C.; Mattern, G. *Chem. Ber.* **1991**, *124*, 1491−1496.
(26) Tacke, R.; Lopez−Mras, A.; Sperlich, J.; Strohmann, C.; Kuhs, W. F.; Mattern, G.; Sebald, A. *Chem. Ber.* **1993**, *126*, 851−861.
(27) Tacke, R.; Becht, J.; Lopez-Mras, A.; Sperlich, J. *J. Organomet. Chem.* **1993**, *446*, 1−8.
(28) Sperlich, J.; Becht, J.; Mühleisen, M.; Wagner, S. A.; Mattern, G.; Tacke, R. *Z. Naturforsch.* **1993**, *48B*, 1693−1706.
(29) Tacke, R.; Becht, J.; Dannappel, O.; Kropfgans, M.; Lopez-Mras, A.; Mühleisen, M.; Sperlich, J. In *Progress in Organosilicon Chemistry*; Marciniec, B., Chojnowski, J., Eds.; Gordon and Breach: Amsterdam, 1995; pp 55−68.
(30) Tacke, R.; Mühleisen, M.; Lopez-Mras, A.; Sheldrick, W. S. *Z. Anorg. Allg. Chem.* **1995**, *621*, 779−788.
(31) Tacke, R.; Heermann, J.; Pülm, M.; Gottfried, E. *Monatsh. Chem.* **1999**, *130*, 99−107.
(32) Tacke, R.; Bertermann, R.; Biller, A.; Dannappel, O.; Pülm, M.; Willeke, R. *Eur. J. Inorg. Chem.* **1999**, 795−805.
(33) Tacke, R.; Bertermann, R.; Biller, A.; Dannappel, O.; Penka, M.; Pülm, M.; Willeke, R. *Z. Anorg. Allg. Chem.* **2000**, *626*, 1159−1173.
(34) Tacke, R.; Wiesenberger, F.; Lopez-Mras, A.; Sperlich, J.; Mattern, G. *Z. Naturforsch.* **1992**, *47B*, 1370−1376.
(35) Tacke, R.; Lopez-Mras, A.; Sheldrick, W. S.; Sebald, A. *Z. Anorg. Allg. Chem.* **1993**, *619*, 347−358.
(36) Tacke, R.; Lopez-Mras, A.; Jones, P. G. *Organometallics* **1994**, *13*, 1617−1623.
(37) Tacke, R.; Heermann, J.; Pülm, M.; Richter, I. *Organometallics* **1998**, *17*, 1663−1668.
(38) Pülm, M.; Willeke, R.; Tacke, R. In *Organosilicon Chemistry IV - From Molecules to Materials*; Auner, N., Weis, J., Eds.; Wiley-VCH: Weinheim, Germany, 2000; pp 478−488.

Scheme 2



Scheme 3



47%)). Subsequent reaction with phenylmagnesium bromide gave the corresponding phenylsilanes **12** (yield 73%) and **13** (yield 71%), which upon treatment with morpholine yielded the (morpholinoalkyl)silanes **14** (yield 67%) and **15** (yield 51%).

The (4-bromophenyl)(chloroalkyl)methoxymethylsilanes **18** and **19** were synthesized according to Scheme 5 by treatment of the (chloroalkyl)dimethoxymethylsilanes **16** and **17** with (4-bromophenyl)magnesium bromide (yields: **18**, 49%; **19**, 54%).

Except for compound **12**,[39] the silanes **2**−**7**, **10**−**15**, **18**, and **19** were obtained as NMR spectroscopically pure products. Their identities were established by elemental analyses (C, H, N), solution NMR studies (^{1}H, ^{13}C, ^{29}Si), and mass spectrometric investigations (EI or CI MS).

Solution-Phase Model Studies. To check the stability of the Si−O bond of alkoxy(aminoalkyl)(4-bromophenyl)organylsilanes under the reaction conditions of a palladium-catalyzed cross coupling with arylzinc reagents, the (4-bromophenyl)silane **15** was treated with (4-fluorophenyl)zinc bromide (obtained by transmetalation of zinc bromide with (4-fluorophenyl)magnesium bromide). The reaction was performed in tetrahydrofuran at −50 °C in the presence of [1,1′-bis(diphenylphosphino)ferrocene]palladium(II) chloride ($PdCl_2$(dppf)) to give the respective (4′-fluorobiphenyl-4-yl)silane **20** (Scheme 6). As shown by GC/MS studies, no substitution of the methoxy group of **15** by a 4-fluorophenyl moiety occurred under the reaction conditions used, and the product **20** was formed in high yield. However, attempts to isolate **20** by distillation resulted in a poor yield (30%; thermal decomposition due to the high boiling point).

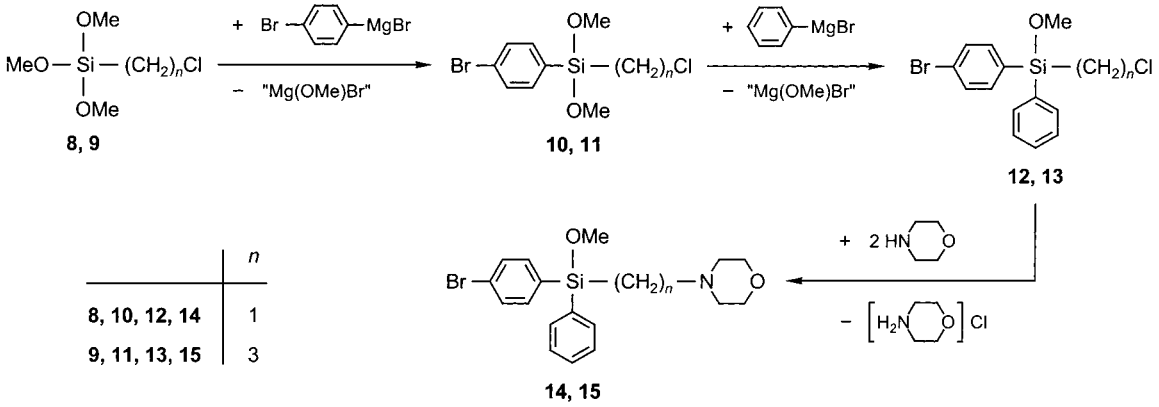
To study the reaction of alkoxy(aminoalkyl)(biphenyl-4-yl)organylsilanes with *vic*-diols (resulting in formation of the respective zwitterionic (ammonioalkyl)bis[diolato(2−)]silicates), the silane **5** was treated with 1,2-dihydroxybenzene (molar ratio 1:2) to give the zwitterionic λ^5*Si*-silicate **21**[40] (Scheme 7). Treatment of the silane **6** with 2 molar equiv of 1,2-dihydroxybenzene and glycolic acid, respectively, gave the zwitterionic λ^5*Si*-silicates **22** and **23** (Scheme 7). All reactions were performed in acetonitrile at room temperature, and compounds **21**−**23** were isolated as colorless crystalline solids (yield: **21**, 92%; **22**, 78%; **23**, 81%). The formation of these products involves cleavage of one Si−O bond (formation of ethanol) and two Si−C bonds (formation of benzene and biphenyl; identified by GC/MS experiments).

Further model studies were carried out under the conditions of a Heck reaction. For this purpose, the (4-bromophenyl)silane **15** was treated with methyl acrylate, triethylamine, and palladium(II) chloride/triphenylphosphane ($PdCl_2$/PPh_3) (as catalyst) in dimethylformamide at 110 °C to give the respective {4-[(*E*)-2-(methoxycarbonyl)vinyl]phenyl}silane **24** (Scheme 8). As shown by GC/MS studies, no substitution of the methoxy group of **15** occurred under the reaction conditions used, and the product **24** was formed in good yield, along with the byproducts methyl cinnamate and methoxydiphenyl(3-morpholinopropyl)silane. Attempts to isolate **24** by distillation resulted in a poor yield (33%; thermal decomposition due to the high boiling point). Subsequent treatment of the silane **24** with 1,2-dihydroxybenzene in acetonitrile at room temperature gave the cleavage products methanol, benzene, and methyl cinnamate

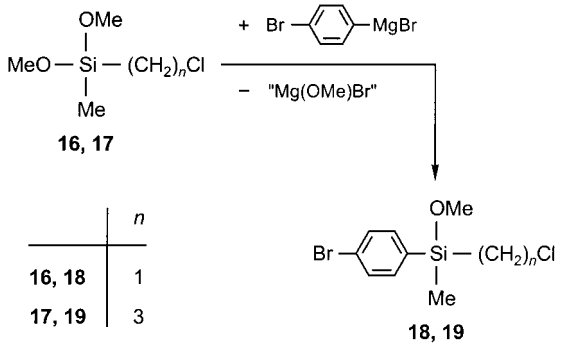
(39) Compound **12** could not be isolated as an NMR spectroscopically pure product; it contained ca. 7 mol % of (bromomethyl)(4-bromophenyl)methoxyphenylsilane (formed by Cl/Br exchange at the $SiCH_2Cl$ group of **12**).

(40) For alternative syntheses of this compound, see ref 28.

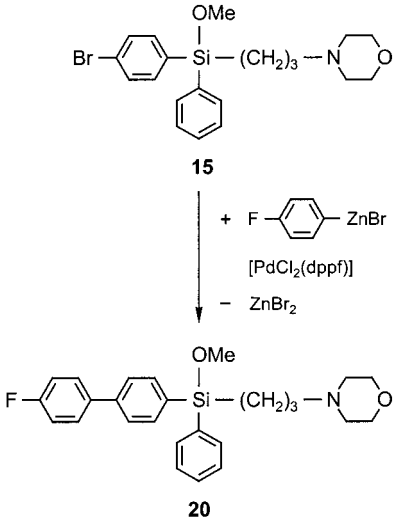
Scheme 4



Scheme 5



Scheme 6



(identified by GC/MS studies), along with the zwitterionic λ^5*Si*-silicate **25**[40] (yield 65%).

The identities of compounds **20**−**25** were established by elemental analyses (C, H, N), solution NMR studies (^{1}H, ^{13}C, ^{29}Si), and mass spectrometric investigations (**20**, CI MS; **21**−**23** and **25**, APCI MS; **24**, EI MS). In addition, the zwitterionic λ^5*Si*-silicates **21**−**23** were structurally characterized by crystal structure analyses and solid-state ^{29}Si VACP/MAS NMR experiments.

Crystal Structure Analyses of 21−**23.** The crystal structures of compounds **21**−**23** were determined by single-crystal X-ray diffraction. The crystal data and experimental parameters used for the crystal structure analyses are given in Table 1 (for further details, see Experimental Section). In the case of **21** there are two zwitterions (*molecules 1* and *2*) in the asymmetric unit, the structures of these molecules being very similar. The molecular structures of **21** (*molecule 1*), **22**, and **23** are shown in Figures 1−3. Selected interatomic distances and angles are given in Table 2.

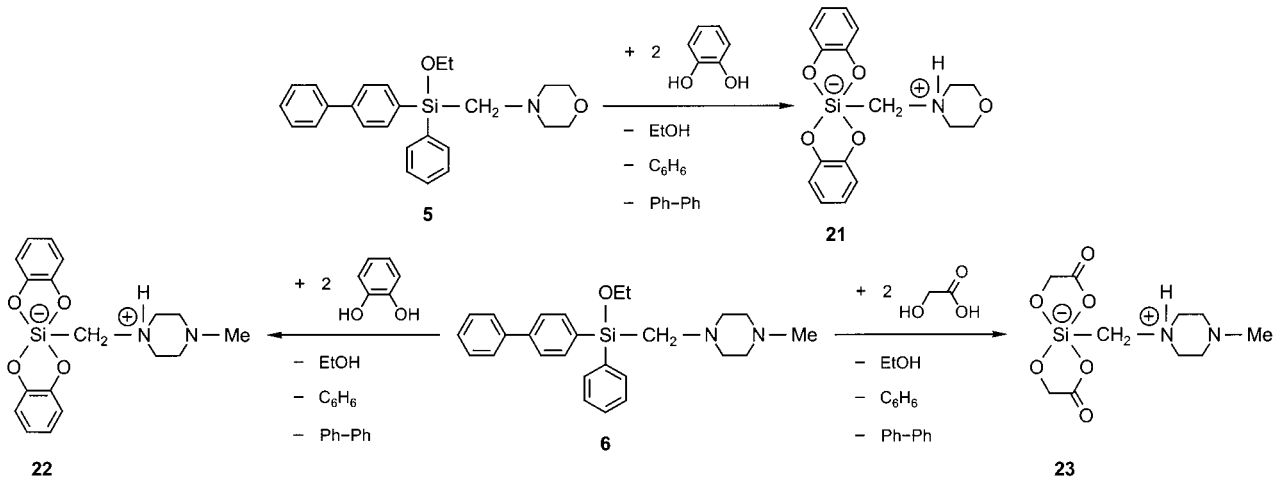
As can be seen from Figures 1−3 and Table 2, the Si-coordination polyhedra of **21**−**23** are distorted trigonal bipyramids, each bidentate diolato(2−) ligand spanning one axial and one equatorial site. In all cases the sum of the equatorial bond angles is 360°, indicating that the silicon atom lies in the plane generated by the three equatorial ligand atoms.

As expected from the presence of their potential NH donor functions and potential oxygen acceptor atoms, compounds **21**−**23** form N−H···O hydrogen bonds in the crystal (Table 3). For **21** bifurcate N−H···O3/O3A and N′−H′···O3′/O3A′ hydrogen bonds were observed, the intermolecular N−H···O3A and N′−H′···O3A′ interactions leading to the formation of centrosymmetric dimers built up by two *molecules 1* or two *molecules 2*. Bifurcate N1−H1···O3/O4A hydrogen bonds, with intermolecular N1−H1···O4A interactions, result in the formation of infinite chains along the [010] axis in the crystal of **22**. For **23** trifurcate N1−H1···O3/O2A/O3A hydrogen bonds were observed, the intermolecular N1−H1···O2A and N1−H1···O3A interactions leading to the formation of centrosymmetric dimers.

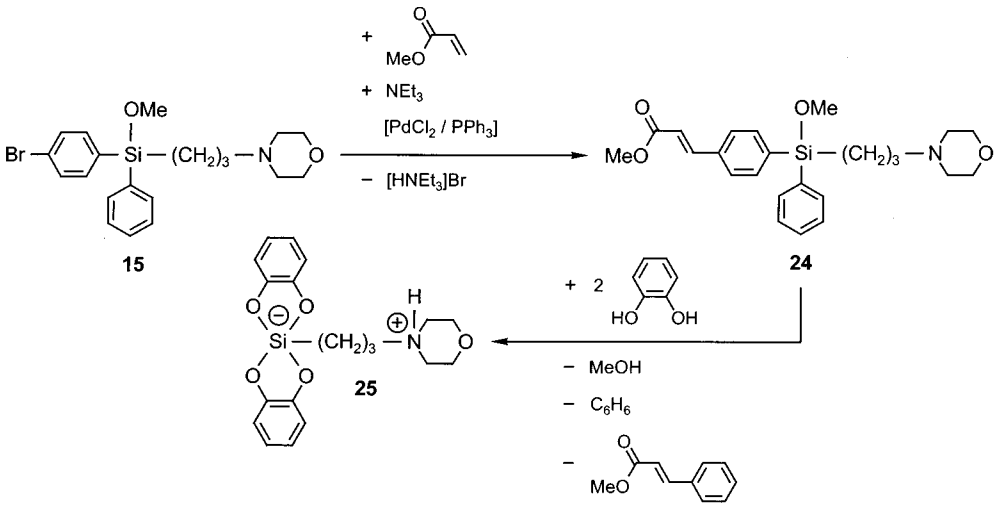
NMR Studies of 21−**23.** Compounds **21**−**23** were studied by ^{29}Si VACP/MAS NMR experiments in the solid state and by ^{1}H, ^{13}C, and ^{29}Si NMR experiments in solution (solvent [D$_6$]DMSO) (see Table 4 and Experimental Section). The isotropic ^{29}Si chemical shifts obtained in the solid-state NMR studies clearly characterize these ^{29}Si resonances as arising from pentacoordinate silicon atoms, in accordance with the results of the crystal structure analyses. As these ^{29}Si chemical shifts are very similar to those observed for compounds **21**−**23** in solution (maximum deviation 1.3 ppm (compound **23**)), it is concluded that pentacoordination is present in solution as well. In addition, the ^{1}H chemical shifts observed for the NH protons (δ 8.8 (**21**), 8.2 (**22**), 8.1 (**23**)) indicate the presence of ammonium groups in solution. Thus, the NMR experiments unequivocally demonstrate that the zwitterions **21**−**23** also exist in solution.

Solid-Phase Syntheses. To test the feasibility of the aforementioned linkage and cleavage strategy under

Scheme 7



Scheme 8



solid-phase conditions, the reaction sequence outlined in Schemes 9 and 10 was studied. In the first step, piperazine was linked to a chloromethyl-substituted Merrifield resin (**26**) to give the piperazinomethyl-substituted resin **27**. For this purpose, **26** was treated with an excess of piperazine in dimethylformamide at 50 °C. As shown by elemental analysis (chlorine content <0.3%), this substitution reaction was almost quantitative under the conditions employed. The NH functionality of **27** was established by IR analysis ($\nu = 3340$ cm^{-1}).

In the next step, resin **27** was treated with an excess of the (chloromethyl)silane **4** and triethylamine in tetrahydrofuran at 50 °C to yield resin **28**. The successful linkage of **4** to the resin was established by solid-state ^{29}Si VACP/MAS NMR experiments (Figure 4). The isotropic ^{29}Si chemical shift of the product **28** (δ −9) is very similar to that observed for the related model compound **6** in solution (δ −11.0; solvent $CDCl_3$).

In the last step, resin **28** was treated with an excess of 1,2-dihydroxybenzene in acetonitrile at 50 °C to yield the cleavage products ethanol, benzene, and biphenyl, along with the λ^5*Si*-silicate-containing resin **29**. Biphenyl was identified by IR and MS studies and isolated in an overall yield of 70% (related to **26**) as a GC-analytically pure product. The identity of the resin-linked pentacoordinate silicate moiety was established by solid-state ^{29}Si VACP/MAS NMR studies (Figure 5). The isotropic ^{29}Si chemical shift of resin **29** (δ −87) is typical of pentacoordinate silicon atoms with an SiO_4C skeleton (in this context, see ref 23) and is very similar to that observed for the related model compound **22** (solid state, δ −85.1; solution in [D_6]DMSO, δ −85.8).

To further test the applicability of the linkage and cleavage strategy outlined in Scheme 10, the NH-functionalized resin **27** was treated with an excess of the (chloroalkyl)silanes **12**, **13**, **18**, or **19** and triethylamine in tetrahydrofuran at 50 °C to yield the respective silane-containing resins **30**−**33** (Scheme 11). Subsequent treatment of these resins with 1,2-dihydroxybenzene in acetonitrile at 50 °C gave the λ^5*Si*-silicate-containing resins **29** and **34**, respectively, along with the cleavage products methanol, benzene (in the case of **30** and **31**), methane (in the case of **32** and **33**), and bromobenzene (Scheme 11). To get some information about the chemical stability of the resins **30**−**33**, cleavage with 1,2-dihydroxybenzene was performed with (i) freshly prepared resin samples and (ii) samples that have been exposed to air for 24 h prior to the cleavage. As reflected by the respective yields of bromobenzene (Table 5), resin **32** proved to be the most suitable one, showing a reasonable stability in the air and leading to good yields of the desired cleavage product within

Table 1. Crystal Data and Experimental Parameters for the Crystal Structure Analyses of 21−23

	21	22	23
empirical formula	$C_{17}H_{19}NO_5Si$	$C_{18}H_{22}N_2O_4Si$	$C_{10}H_{18}N_2O_6Si$
formula mass, g mol^{-1}	345.42	358.47	290.35
collecn *T*, K	173(2)	173(2)	173(2)
λ(Mo Kα), Å	0.710 73	0.710 73	0.710 73
cryst syst	triclinic	orthorhombic	triclinic
space group (No.)	$P\bar{1}$ (2)	*Pbca* (61)	$P\bar{1}$ (2)
a, Å	9.3230(19)	10.093(2)	8.5411(12)
b, Å	9.3468(19)	9.2001(18)	9.1329(17)
c, Å	19.770(4)	37.950(8)	9.6803(17)
V, Å^3	1599.4(6)	3523.8(12)	663.83(19)
Z	4	8	2
D(calcd), g cm^{-3}	1.435	1.351	1.453
μ, mm^{-1}	0.175	0.153	0.202
F(000)	728	1520	308
cryst dimens, mm	0.3 × 0.2 × 0.2	0.4 × 0.2 × 0.2	0.2 × 0.2 × 0.2
2θ range, deg	4.68−46.60	4.58−49.42	4.62−45.94
index ranges	$-10 \le h \le 10$, $-10 \le k \le 10$, $-21 \le l \le 22$	$0 \le h \le 11$, $0 \le k \le 10$, $0 \le l \le 44$	$-9 \le h \le 1$, $-10 \le k \le 9$, $-10 \le l \le 10$
no. of collected rflns	18 678	19 951	2191
no. of indep rflns	4513	2995	1841
R_{int}	0.0800	0.0989	0.0276
no. of rflns used	4513	2995	1841
no. of params	549	315	177
S[a]	0.887	0.963	1.042
weight params *a*/*b*[b]	0.0393/0	0.0636/0	0.0345/0.2956
R1[c] ($I > 2\sigma(I)$)	0.0422	0.0474	0.0487
wR2[d] (all data)	0.0792	0.1139	0.1022
extinction coeff	0.0135(9)	0.0039(5)	0.008(3)
max/min res electron dens, e Å^{-3}	+0.265/−0.304	+0.225/−0.234	+0.461/−0.247

[a] $S = \{\sum[w(F_o^2 - F_c^2)^2]/(n-p)\}^{0.5}$; n = no. of reflections; p = no. of parameters. [b] $w^{-1} = \sigma^2(F_o^2) + (aP)^2 + bP$, with $P = (\max F_o^2, 0 + 2F_c^2)/3$. [c] $R1 = \sum||F_o| - |F_c||/\sum|F_o|$. [d] $wR2 = \{\sum[w(F_o^2 - F_c^2)^2]/\sum[w(F_o^2)^2]\}^{0.5}$.

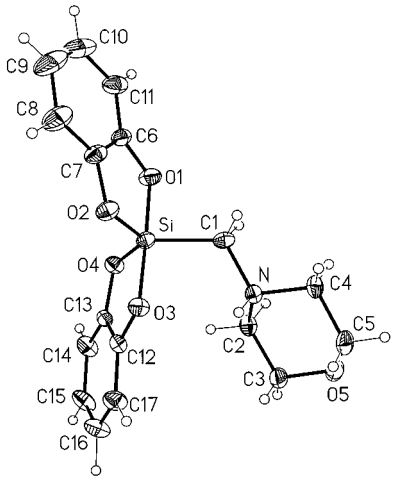


Figure 1. Molecular structure of **21** in the crystal (*molecule 1*, probability level of displacement ellipsoids 50%), showing the atomic numbering scheme.

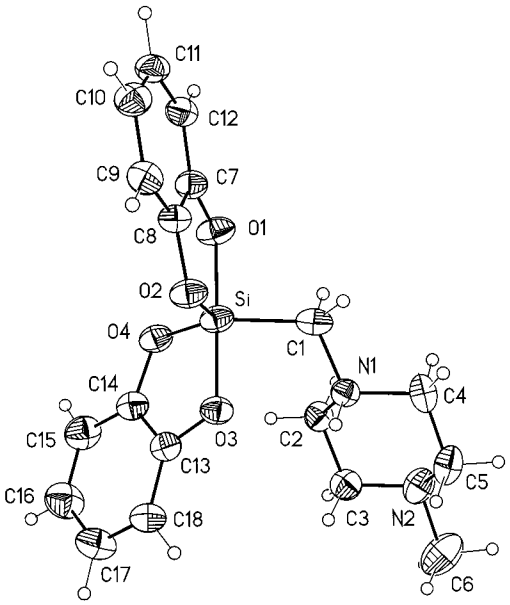


Figure 2. Molecular structure of **22** in the crystal (probability level of displacement ellipsoids 50%), showing the atomic numbering scheme.

acceptable reaction times. Thus, all further investigations were carried out with resin **32**.

To test the stability of this particular linker system under various standard conditions of organic solid-phase synthesis, resin **32** was treated with a series of reagents that are frequently used for this purpose (Table 6). The resulting resins were subsequently treated with 1,2-dihydroxybenzene in acetonitrile at 50 °C, and the yield of the cleavage product bromobenzene was determined by HPLC analysis. The results of these studies are summarized in Table 6. As can be seen from these data, resin **32** is sufficiently stable under various standard conditions of organic solid-phase synthesis; however, there are also reagents that are not compatible with this resin.

To further test the suitability of resin **32** for organic solid-phase synthesis, some palladium-catalyzed cross-coupling reactions were studied. For this purpose, resin **32** was treated with the arylzinc reagents (4-fluorophenyl)zinc bromide, (2-methoxyphenyl)zinc bromide, or (2-thienyl)zinc bromide in the presence of the catalyst $PdCl_2$(dppf) (1 mol %) to yield the respective resins **35**−**37** (Scheme 12). The C−C coupling reactions were performed in tetrahydrofuran (**35**, **36**) or tetrahydrofuran/*n*-hexane (**37**) at −50 °C (→ −10 °C → 20 °C). Subsequent treatment of **35**−**37** with an excess of 1,2-

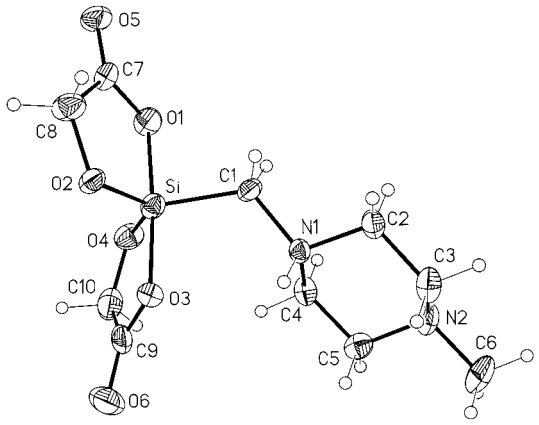


Figure 3. Molecular structure of **23** in the crystal (probability level of displacement ellipsoids 50%), showing the atomic numbering scheme.

Table 2. Selected Interatomic Distances (Å) and Angles (deg) for 21−23

	21			
	molecule 1	molecule 2[a]	**22**	**23**
Si−O1	1.761(2)	1.766(2)	1.766(2)	1.804(3)
Si−O2	1.7080(19)	1.7000(19)	1.6995(19)	1.675(3)
Si−O3	1.797(2)	1.808(2)	1.7733(19)	1.803(3)
Si−O4	1.692(2)	1.6905(18)	1.708(2)	1.651(3)
Si−C1	1.896(3)	1.893(3)	1.901(3)	1.880(4)
O1−Si−O2	89.73(10)	89.96(9)	90.26(9)	88.80(13)
O1−Si−O3	178.08(10)	178.76(9)	179.03(11)	175.18(14)
O1−Si−O4	90.21(10)	90.90(9)	90.17(10)	89.79(14)
O1−Si−C1	87.84(12)	87.58(11)	88.90(12)	88.64(15)
O2−Si−O3	88.69(10)	88.82(9)	89.26(9)	87.36(13)
O2−Si−O4	120.68(10)	117.97(10)	118.41(10)	122.75(14)
O2−Si−C1	118.92(12)	121.13(11)	119.20(13)	116.49(16)
O3−Si−O4	89.66(9)	89.87(9)	89.32(9)	89.85(14)
O3−Si−C1	93.88(11)	92.86(11)	92.07(11)	95.67(14)
O4−Si−C1	120.36(12)	120.87(11)	122.39(12)	120.68(16)

[a] Atoms of *molecule 2*: Si′, O1′, O2′, O3′, O4′, and C1′.

Table 3. Geometric Data[a] for the N−H···O Hydrogen Bonds in the Crystals of 21−23

compd	N−H···O	N···O, Å	N−H, Å	H···O, Å	N−H···O, deg
21[b]	N−H···O3 (intra)	2.816(3)	0.85(4)	2.37(3)	113(3)
	N−H···O3A (inter)	3.031(4)	0.85(4)	2.32(4)	141(2)
	N′−H′···O3′ (intra)	2.806(3)	0.91(4)	2.41(3)	106(2)
	N′−H′···O3A′ (inter)	3.042(3)	0.91(4)	2.18(4)	157(2)
22[c]	N1−H1···O3 (intra)	2.742(3)	0.90(3)	2.31(3)	109(2)
	N1−H1···O4A (inter)	3.197(3)	0.90(3)	2.33(3)	163(2)
23[d]	N1−H1···O3 (intra)	2.900(4)	0.89(4)	2.50(4)	108(3)
	N1−H1···O2A (inter)	2.976(4)	0.89(4)	2.12(4)	161(3)
	N1−H1···O3A (inter)	3.111(4)	0.89(4)	2.52(4)	125(4)

[a] Data calculated by using the program PLATON.[41] [b] O3···H···O3A (*molecule 1*), 80.0(9)°; O3′···H′···O3A′ (*molecule 2*), 86.9(12)°. [c] O3···H1···O4A, 85.3(10)°. [d] O3···H1···O2A, 91.3(13)°; O3···H1···O3A, 75.3(11)°; O2A···H1···O3A, 61.7(9)°.

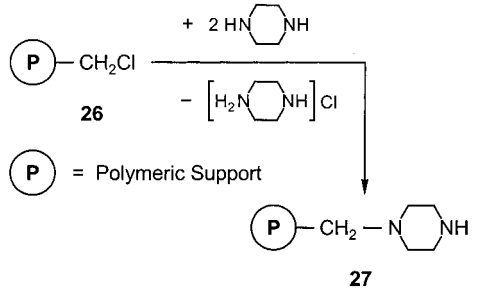
Table 4. ^{29}Si NMR Data for 21−23 in the Crystal and in Solution[a]

compd	$\delta(^{29}\mathrm{Si})$ (cryst)[b]	$\delta(^{29}\mathrm{Si})$ (soln)[c]
21	−85.5	−85.8
22	−85.1	−85.8
23	−89.0	−90.3

[a] Chemical shifts in ppm; spectra recorded at 22 °C. [b] Isotropic chemical shifts obtained by solid-state ^{29}Si VACP/MAS NMR experiments. [c] Solvent [D$_6$]DMSO.

dihydroxybenzene in acetonitrile at 50 °C yielded the cleavage products methanol, methane, 4-fluorobiphenyl (educt **35**), 2-methoxybiphenyl (educt **36**), and 2-phenylthiophene (educt **37**), along with the λ^5*Si*-silicate-containing resin **29** (Scheme 12). The biaryl cleavage products 4-fluorobiphenyl (yield 57%), 2-methoxybiphenyl (yield 53%), and 2-phenylthiophene (yield 35%) were isolated as GC analytically pure products (yields related to the chloromethyl-substituted Merrifield resin (**26**)), and their identities were established by solution NMR studies (^{1}H, ^{13}C) and mass spectrometric investigations.

Scheme 9



Finally, a solid-phase synthesis based on the Heck reaction was studied on the analytical scale. For this purpose, resin **32** was treated with methyl acrylate, triethylamine, and $PdCl_2/PPh_3$ (as catalyst) in dimethylformamide at 110 °C to yield the silane-containing resin **38** (Scheme 13). Subsequent treatment of **38** with 1,2-dihydroxybenzene in acetonitrile at 50 °C gave the cleavage products methanol, methane, and methyl cinnamate (identified by GC/MS studies), along with the λ^5*Si*-silicate-containing resin **29** (Scheme 13). These results again emphasize the high synthetic potential of the silicon-based linkage and cleavage strategy developed in this study.

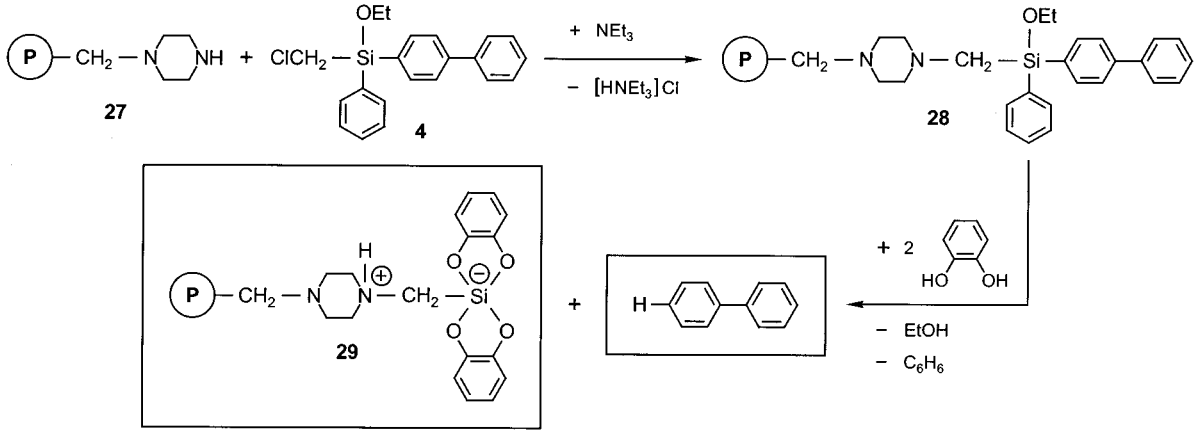
It is obvious that the field of application of this novel method can be extended significantly (i) by using other *vic*-diols instead of 1,2-dihydroxybenzene as cleavage reagent and (ii) by applying this linkage and cleavage strategy to germanium chemistry. Preliminary studies in our laboratory support this concept.

Experimental Section

General Procedures. Except for the workup procedures in context with the solid-phase cleavage reactions, all syntheses were carried out under dry nitrogen. The organic solvents used were dried and purified according to standard procedures and stored under dry nitrogen. Melting (decomposition) points were determined with a Leitz Biomed microscope equipped with a heater (Leitz, Model M 350). The ^{1}H, ^{13}C, ^{19}F, and ^{29}Si solution NMR spectra were recorded at 22 °C on a Bruker DRX-300 NMR spectrometer (^{1}H, 300.1 MHz; ^{13}C, 75.5 MHz; ^{19}F, 282.4 MHz; ^{29}Si, 59.6 MHz). $CDCl_3$ and [D$_6$]DMSO were used as solvents. Chemical shifts were determined relative to internal TMS (^{1}H, δ 0; ^{13}C, δ 0; ^{29}Si, δ 0) or external $CFCl_3$ (^{19}F, δ 0). Assignment of the ^{1}H NMR data was supported by ^{1}H,^{1}H COSY and ^{13}C,^{1}H correlation experiments. Assignment of the ^{13}C NMR data was supported by DEPT 135 and ^{13}C,^{1}H correlation experiments. Solid-state ^{29}Si VACP/MAS NMR experiments were recorded at 22 °C on a Bruker DSX-400 NMR spectrometer with bottom layer rotors of ZrO_2 (diameter 7 mm) containing ca. 200 mg of sample (79.5 MHz; external standard TMS, δ 0; spinning rate, 5 kHz; contact time, 5 ms; 90° ^{1}H transmitter pulse length, 3.6 μs; repetition time, 4 s;

(41) Hydrogen bonding systems were analyzed by using the program PLATON: Spek, A. L. PLATON; University of Utrecht, The Netherlands, 1998.

Scheme 10



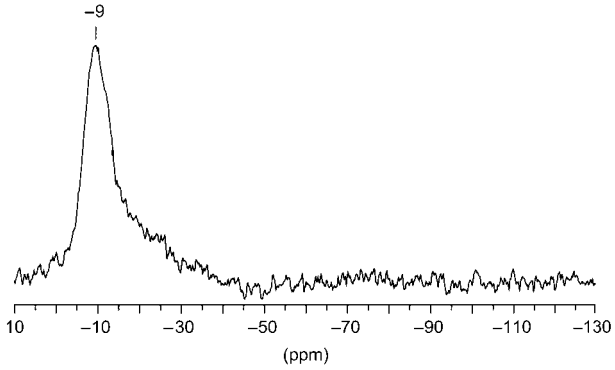


Figure 4. ^{29}Si VACP/MAS NMR spectrum (17 124 transients) of the resin **28** (for details, see the Experimental Section).

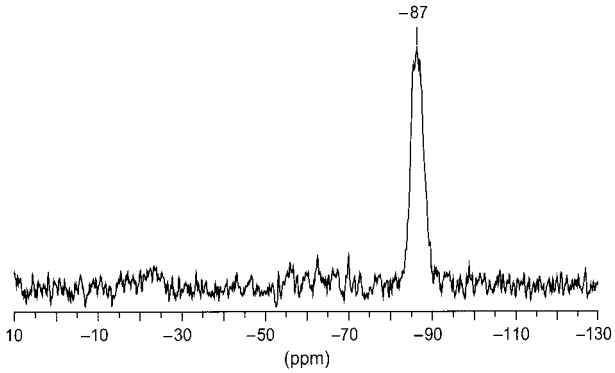


Figure 5. ^{29}Si VACP/MAS NMR spectrum (1017 transients) of the resin **29** (for details, see the Experimental Section).

no. of transients, 20−400 (**21**−**23**, **25**) or 1000−25 000 (**28**−**38**)). Mass spectra (EI MS, 70 eV; CI MS, reactant gas methane; APCI MS, cone voltage 23 V, nebulizer temperature 650 °C, needle voltage 3000 V) were recorded with a ThermoQuest Trio 1000 mass spectrometer. Sample injection for the APCI MS experiments was carried out by means of a Rheodyne injection valve (Model 7725i) with a 20 μL sample loop (Merck-Hitachi HPLC pump, Model L-7100; solvent, acetonitrile; flow rate, 1.0 mL min^{-1}). The selected *m*/*z* values given refer to the isotopes ^{1}H, ^{12}C, ^{14}N, ^{16}O, ^{19}F, ^{28}Si, ^{35}Cl, and ^{79}Br. IR spectra were obtained with a Bruker Equinox 55 IR spectrometer. GC investigations were performed with a CE Instruments gas chromatograph, Model GC 8060. HPLC studies were carried out with a Merck-Hitachi L-6200 instrument equipped with a Merck LiChroCART 125-4 cartridge (charged with Merck LiChrospher 100 RP-18, 5 μm), a Merck-Hitachi L-4200 UV−vis detector, and a Merck-Hitachi D-2000 chromato-integrator. A Büchi GKR 50 apparatus was used for the Kugelrohr distillations and solid-phase syntheses (the reported temperatures refer to the respective oven temperatures). (Chloromethyl)trimethoxysilane[42] (**8**) and (chloromethyl)dimethoxy(methyl)silane[25] (**16**) were prepared according to published procedures. Trichloro(chloromethyl)silane (**1**), (3-chloropropyl)trimethoxysilane (**9**), and (3-chloropropyl)dimethoxymethylsilane (**17**) were purchased from Aldrich. Chloromethyl-substituted Merrifield resin (**26**, substitution 1.08 mmol g^{-1}) was purchased from NovaBiochem.

Preparation of (Chloromethyl)triethoxysilane (2). Ethanol (181 g, 3.93 mol) was added dropwise at −30 °C within 1.5 h to a stirred solution of **1** (200 g, 1.09 mol) in *n*-pentane (500 mL). During the addition, a strong stream of nitrogen gas was passed through the mixture. After complete addition, the reaction mixture was stirred for another 16 h at room temperature while still passing nitrogen through the solution. The solvent and the excess ethanol were removed by distillation (normal pressure), and the residue was distilled under reduced pressure (Vigreux column, 20 cm) to give **2** in 80% yield as a colorless liquid (186 g, 874 mmol); bp 91 °C/33 mbar. ^{1}H NMR ($CDCl_3$): δ 1.25 (t, $^{3}J_{HH}$ = 7.0 Hz, 9 H, CCH_3), 2.80 (s, 2 H, SiCH_2Cl), 3.91 (q, $^{3}J_{HH}$ = 7.0 Hz, 6 H, CCH_2O). ^{13}C NMR ($CDCl_3$): δ 18.2 (CCH_3), 23.8 (SiCH_2Cl), 59.4 (CCH_2O). ^{29}Si NMR ($CDCl_3$): δ −58.0. EI MS: *m*/*z* 211 (1%, M^+ − H), 197 (3%, M^+ − CH_3), 163 (100%, M^+ − CH_2Cl). Anal. Calcd for $C_7H_{17}ClO_3Si$: C, 39.52; H, 8.05. Found: C, 39.6; H, 8.0.

Preparation of (Biphenyl-4-yl)(chloromethyl)diethoxysilane (3). A Grignard reagent was prepared from 4-bromobiphenyl (22.2 g, 95.2 mmol) and magnesium turnings (2.31 g, 95.0 mmol) in THF (100 mL) and then added dropwise at 0 °C within 3 h to a stirred solution of **2** (20.3 g, 95.4 mmol) in THF (50 mL). The reaction mixture was then stirred for 20 h at room temperature and for 3 h under reflux. The solvent was removed under reduced pressure and *n*-pentane (100 mL) added to the residue. The resulting precipitate was filtered off, the solvent removed under reduced pressure, and the residue distilled in vacuo (Vigreux column, 10 cm) to give **3** in 65% yield as a colorless liquid (19.9 g, 62.0 mmol); bp 133 °C/0.05 mbar. ^{1}H NMR ($CDCl_3$): δ 1.29 (t, $^{3}J_{HH}$ = 6.8 Hz, 6 H, CCH_3), 3.01 (s, 2 H, SiCH_2Cl), 3.94 (q, $^{3}J_{HH}$ = 6.8 Hz, 4 H, CCH_2O), 7.30−7.80 (m, 9 H, $C_{12}H_9$). ^{13}C NMR ($CDCl_3$): δ 18.3 (CCH_3), 25.9 (SiCH_2Cl), 59.4 (CCH_2O), 126.7, 127.1, 128.8, and 135.1 (*C*-2/*C*-3/*C*-5/*C*-6/*C*-2′/*C*-3′/*C*-5′/*C*-6′, $C_{12}H_9$), 127.6 (*C*-4′, $C_{12}H_9$), 129.6 (*C*-4, $C_{12}H_9$), 140.7 and 143.4 (*C*-1/*C*-1′, $C_{12}H_9$). ^{29}Si NMR ($CDCl_3$): δ −31.4. EI MS: *m*/*z* 320 (6%, M^+), 271 (100%, M^+ − CH_2Cl). Anal. Calcd for $C_{17}H_{21}ClO_2Si$: C, 63.63; H, 6.60. Found: C, 63.6; H, 6.6.

(42) Tacke, R.; Pikies, J.; Linoh, H.; Rohr-Aehle, R.; Gönne, S. *Liebigs Ann. Chem.* **1987**, 51−57.

Scheme 11

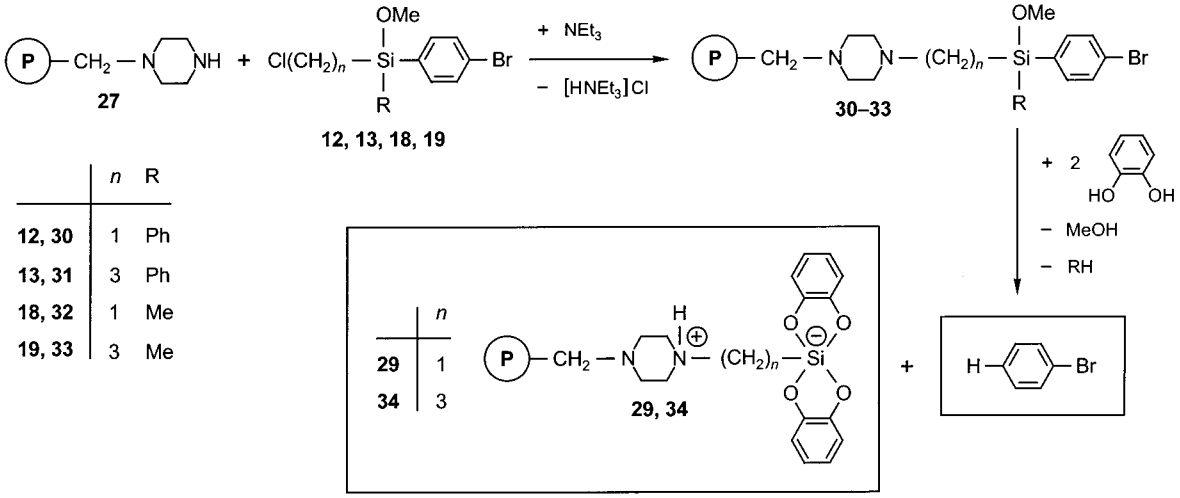


Table 5. Yields (%) of Bromobenzene Obtained by Treatment of Resins 30−33 with 1,2-Dihydroxybenzene[a]

	30	31	32	33
entry 1[b]	70	39	66	27
entry 2[c]	56	39	61	27

[a] The cleavage reactions were performed by treatment of a suspension of the respective resin (100 mg) in acetonitrile (3.0 mL) with 5 molar equiv (related to the respective silane moieties) of 1,2-dihydroxybenzene at 50 °C for 20 h. The yields of bromobenzene (related to the respective resin) were determined by HPLC analysis using a 3.06 mM solution of anthracene in tetrahydrofuran as internal standard. [b] The cleavage was performed with a freshly prepared resin. [c] The cleavage was performed with a resin that had been exposed to air for 24 h and then dried in vacuo at room temperature.

Table 6. Yields (%) of Bromobenzene Obtained after Treatment of Resin 32 with Various Reagents and Subsequent Treatment with 1,2-Dihydroxybenzene[a]

entry	reagent	quantity	yield[b]
1	CF_3COOH	61.6 mg	86
2	2 M aqueous NaOH soln	270 μL	61
3	$NaBH_4$	20.4 mg	69
4	1 M BH_3 soln in THF	540 μL	0
5	PPh_3Br_2	228 mg	0
6	3 M HCl soln in Et_2O	180 μL	0
7	3-chloroperbenzoic acid (stabilized with 10% 3-chlorobenzoic acid and 35% H_2O)	169 mg	0
8	KO-*t*-Bu	60.6 mg	79
9	2 M aqueous HCl soln	270 μL	0
10	NaOMe	29.2 mg	98
11	NaOAc/glacial HOAc	44.3 mg/ 32.4 mg	69
12	heating to 100 °C (solvent toluene)		74
13	$AlCl_3$, reflux (solvent CH_2Cl_2)	72.0 mg	0
14	Na_2CO_3	57.2 mg	88
15	*n*-BuLi (1.6 M soln in hexane)	340 μL	21
16	reference[c]		100

[a] If not stated otherwise, a suspension of resin **32** (100 mg, corresponding to 108 μmol of resin-linked silane) in tetrahydrofuran (5 mL) was treated with 5 molar equiv (related to the resin-linked silane) of the respective reagent at 50 °C for 20 h. After removal of the reagent by filtration, the resin was dried in vacuo and then treated with a solution of 5 molar equiv (related to the resin-linked silane) of 1,2-dihydroxybenzene in acetonitrile (3.0 mL) at 50 °C for 20 h. [b] The yield of bromobenzene (in %) was determined by HPLC analysis; the yield obtained according to entry 16 served as reference (100%). [c] Resin **32** was only treated with 5 molar equiv (related to the resin-linked silane) of 1,2-dihydroxybenzene in acetonitrile at 50 °C for 20 h (no pretreatment with any reagent).

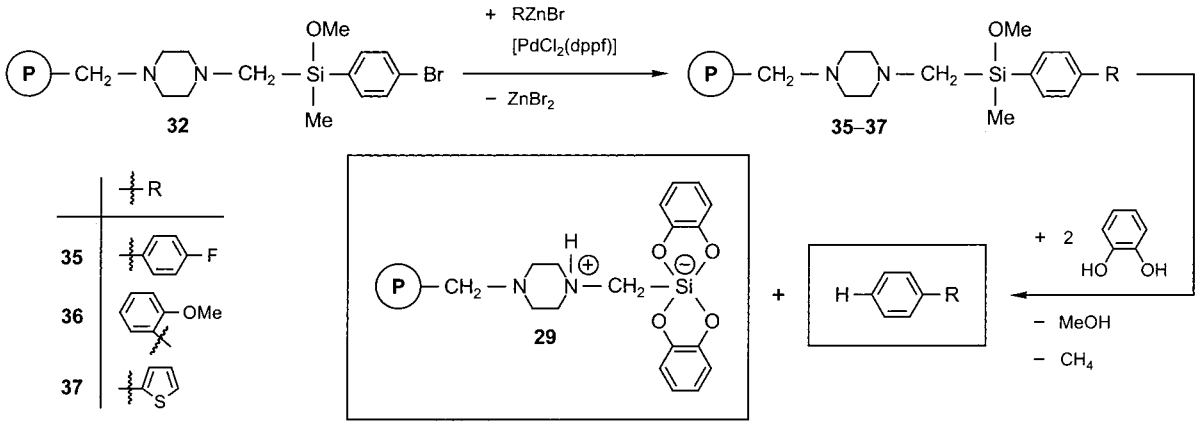
Preparation of (Biphenyl-4-yl)(chloromethyl)ethoxyphenylsilane (4). The synthesis was carried out analogously to that of **3**, starting from a solution of **3** (9.63 g, 30.0 mmol) in THF (20 mL) and a Grignard reagent prepared from bromobenzene (4.71 g, 30.0 mmol) and magnesium turnings (729 mg, 30.0 mmol) in THF (30 mL) to give **4** in 69% yield as a colorless liquid (7.31 g, 20.7 mmol); bp 181−182 °C/0.001 mbar. ^{1}H NMR ($CDCl_3$): δ 1.38 (t, $^3J_{HH}$ = 6.8 Hz, 3 H, CCH_3), 3.41 (s, 2 H, SiCH_2Cl), 4.02 (q, $^3J_{HH}$ = 6.8 Hz, 2 H, CCH_2O), 7.40−7.87 (m, 14 H, C$_6H_5$, C$_{12}H_9$). ^{13}C NMR ($CDCl_3$): δ 18.3 (CCH_3), 27.4 (SiCH_2Cl), 60.1 (CCH_2O), 126.7, 127.1, 128.0, 128.8, 134.8, and 135.3 (*C*-2/*C*-3/*C*-5/*C*-6, C_6H_5; *C*-2/*C*-3/*C*-5/*C*-6/*C*-2′/*C*-3′/*C*-5′/*C*-6′, $C_{12}H_9$), 127.6 and 130.5 (*C*-4, C_6H_5; *C*-4′, $C_{12}H_9$), 131.0 and 132.4 (*C*-1, C_6H_5; *C*-4, $C_{12}H_9$), 140.7 and 143.1 (*C*-1/*C*-1′, $C_{12}H_9$). ^{29}Si NMR ($CDCl_3$): δ −13.3. EI MS: *m*/*z* 352 (8%, M^+), 303 (100%, $M^+ - CH_2Cl$). Anal. Calcd for $C_{21}H_{21}ClOSi$: C, 71.47; H, 6.00. Found: C, 71.3; H, 6.0.

Preparation of (Biphenyl-4-yl)ethoxy(morpholinomethyl)phenylsilane (5). Method A. A solution of **4** (1.00 g, 2.83 mmol) and morpholine (732 mg, 8.40 mmol) in toluene (20 mL) was stirred under reflux for 24 h. After the mixture was cooled to room temperature, the solvent and the excess morpholine were removed under reduced pressure, and *n*-pentane (10 mL) was added to the residue. The resulting precipitate was filtered off, the solvent removed from the filtrate under reduced pressure, and the residue distilled in vacuo to give **5** in 54% yield as a yellowish oily liquid (623 mg, 1.54 mmol); bp 213 °C/0.03 mbar. For analytical data, see below.

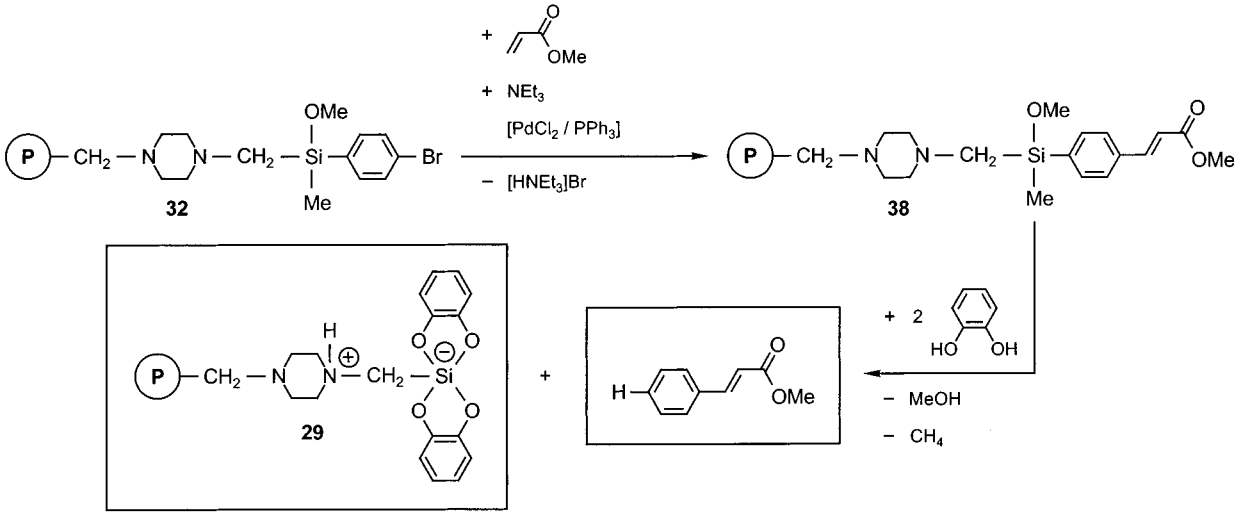
Method B. The synthesis was carried out analogously to that of **3**, starting from a solution of **7** (5.70 g, 15.3 mmol) in THF (20 mL) and a Grignard reagent prepared from bromobenzene (2.41 g, 15.3 mmol) and magnesium turnings (373 mg, 15.3 mmol) in THF (20 mL) to give **5** in 51% yield as a yellowish oily liquid (3.17 g, 7.85 mmol); bp 213 °C/0.03 mbar. ^{1}H NMR ($CDCl_3$): δ 1.24 (t, $^3J_{HH}$ = 7.0 Hz, 3 H, CCH_3), 2.41−2.56 (m, 6 H, SiCH_2N, CCH_2N), 3.60−3.72 (m, 4 H, NCCH_2O), 3.85 (q, $^3J_{HH}$ = 7.0 Hz, 2 H, CCH_2OSi), 7.31−7.78 (m, 14 H, C$_6H_5$, C$_{12}H_9$). ^{13}C NMR ($CDCl_3$): δ 18.4 (CCH_3), 48.4 (SiCH_2N), 57.4 (CCH_2N), 59.7 (CCH_2OSi), 67.2 (NCCH_2O), 126.5, 127.1, 127.8, 128.7, 134.7, and 135.2 (*C*-2/*C*-3/*C*-5/*C*-6, C_6H_5; *C*-2/*C*-3/*C*-5/*C*-6/*C*-2′/*C*-3′/*C*-5′/*C*-6′, $C_{12}H_9$), 127.5 and 130.0 (*C*-4, C_6H_5; *C*-4′, $C_{12}H_9$), 133.5 and 135.0 (*C*-1, C_6H_5; *C*-4, $C_{12}H_9$), 140.9 and 142.6 (*C*-1/*C*-1′, $C_{12}H_9$). ^{29}Si NMR ($CDCl_3$): δ −10.7. CI MS (positive ions): *m*/*z* 404 (100%, $[M + H]^+$). Anal. Calcd for $C_{25}H_{29}NO_2Si$: C, 74.40; H, 7.24; N, 3.47. Found: C, 74.5; H, 7.2; N, 3.5.

Preparation of (Biphenyl-4-yl)ethoxy[(4-methylpiperazin-1-yl)methyl]phenylsilane (6). A mixture of 1-meth-

Scheme 12



Scheme 13



ylpiperazine (1.70 g, 17.0 mmol) and **4** (2.00 g, 5.67 mmol) was stirred at room temperature for 8 days. After addition of *n*-pentane (5 mL), the resulting mixture was stirred for another 24 h at room temperature, and again *n*-pentane (5 mL) was added. The resulting precipitate was filtered off, the excess 1-methylpiperazine and the solvent were removed from the filtrate under reduced pressure, and the residue was distilled in vacuo to give **6** in 91% yield as a yellowish oily liquid (2.14 g, 5.14 mmol); bp 207−208 °C/0.002 mbar. ^{1}H NMR ($CDCl_3$): δ 1.24 (t, $^3J_{HH}$ = 6.8 Hz, 3 H, CCH_3), 2.04−2.82 (m, 8 H, CCH_2N), 2.24 (s, 3 H, NCH_3), 2.53 (s, 2 H, SiCH_2N), 3.85 (q, $^3J_{HH}$ = 6.8 Hz, 2 H, CCH_2O), 7.27−7.84 (m, 14 H, C_6H_5, $C_{12}H_9$). ^{13}C NMR ($CDCl_3$): δ 18.4 (CCH_3), 46.0 (NCH_3), 47.8 (SiCH_2N), 55.5 and 57.0 (CCH_2N), 59.6 (CCH_2O), 126.4, 127.1, 127.8, 128.7, 134.8, and 135.3 (*C*-2/*C*-3/*C*-5/*C*-6, C_6H_5; *C*-2/*C*-3/*C*-5/*C*-6/*C*-2′/*C*-3′/*C*-5′/*C*-6′, $C_{12}H_9$), 127.4 and 129.9 (*C*-4, C_6H_5; *C*-4′, $C_{12}H_9$), 133.7 and 135.0 (*C*-1, C_6H_5; *C*-4, $C_{12}H_9$), 140.9 and 142.4 (*C*-1/*C*-1′, $C_{12}H_9$). ^{29}Si NMR ($CDCl_3$): δ −11.0. EI MS: *m*/*z* 416 (42%, M^+), 346 (75%, $M^+ - C_4H_8N$), 70 (100%, $C_4H_8N^+$). Anal. Calcd for $C_{26}H_{32}N_2OSi$: C, 74.95; H, 7.74; N, 6.72. Found: C, 74.8; H, 7.7; N, 6.6.

Preparation of (Biphenyl-4-yl)diethoxy(morpholinomethyl)silane (7). The synthesis was carried out analogously to that of **5** (method A, reaction time 48 h), starting from a solution of **3** (10.0 g, 31.2 mmol) and morpholine (8.50 g, 97.6 mmol) in toluene (80 mL) to give **7** in 76% yield as a colorless liquid (8.79 g, 23.7 mmol); bp 165−166 °C/0.05 mbar. ^{1}H NMR ($CDCl_3$): δ 1.26 (δ_X), 3.88 (δ_A), and 3.90 (δ_B) ($^2J_{AB}$ = 10.3 Hz, $^3J_{AX}$ = 7.0 Hz, $^3J_{BX}$ = 7.0 Hz, 10 H, SiOCH_AH_BC(H_X)$_3$), 2.22 (s, 2 H, SiCH_2N), 2.43−2.50 (m, 4 H, CCH_2N), 3.61−3.69 (m, 4 H, NCCH_2O), 7.30−7.80 (m, 9 H, $C_{12}H_9$). ^{13}C NMR ($CDCl_3$): δ 18.4 (CCH_3), 47.1 (SiCH_2N), 57.3 (CCH_2N), 58.9 (CCH_2OSi), 67.2 (NCCH_2O), 126.6, 127.2, 128.8, and 134.9 (*C*-2/*C*-3/*C*-5/*C*-6/*C*-2′/*C*-3′/*C*-5′/*C*-6′, $C_{12}H_9$), 127.5 (*C*-4′, $C_{12}H_9$), 132.3 (*C*-4, $C_{12}H_9$), 140.9 and 142.8 (*C*-1/*C*-1′, $C_{12}H_9$). ^{29}Si NMR ($CDCl_3$): δ −26.2. CI MS (positive ions): *m*/*z* 372 (100%, $[M + H]^+$). Anal. Calcd for $C_{21}H_{29}NO_3Si$: C, 67.89; H, 7.87; N, 3.77. Found: C, 67.8; H, 7.7; N, 3.8.

Preparation of (4-Bromophenyl)(chloromethyl)dimethoxysilane (10). A Grignard reagent was prepared from 1,4-dibromobenzene (41.3 g, 175 mmol) and magnesium turnings (4.25 g, 175 mmol) in diethyl ether (150 mL) and then added dropwise at 0 °C within 3 h to a stirred solution of **8** (29.9 g, 175 mmol) in diethyl ether (80 mL). The reaction mixture was then stirred for 20 h at room temperature and for 3 h under reflux. The solvent was removed under reduced pressure, *n*-pentane (80 mL) added to the residue, and the resulting mixture stirred under reflux for 1 h. The resulting precipitate was filtered off and the solvent removed from the filtrate under reduced pressure. The unreacted 1,4-dibromobenzene was removed from the residue by sublimation in vacuo and compound **10** isolated by distillation in vacuo (Vigreux column, 10 cm) in 46% yield as a colorless liquid (23.9 g, 80.8 mmol); bp 86−87 °C/0.1 mbar. ^{1}H NMR ($CDCl_3$): δ 2.97 (s, 2 H, SiCH_2Cl), 3.64 (s, 6 H, OCH_3), 7.49−7.58 (m, 4 H, C_6H_4-Br). ^{13}C NMR ($CDCl_3$): δ 25.0 (SiCH_2Cl), 51.3 (OCH_3), 126.1 and 128.9 (*C*-1/*C*-4, C_6H_4Br), 131.4 and 136.2 (*C*-2/*C*-3/*C*-5/*C*-6, C_6H_4Br). ^{29}Si NMR ($CDCl_3$): δ −28.9. EI MS: *m*/*z* 294 (1%, M^+), 245 (100%, $M^+ - CH_2Cl$). Anal. Calcd for $C_9H_{12}BrClO_2Si$: C, 36.56; H, 4.09. Found: C, 36.7; H, 4.0.

Preparation of (4-Bromophenyl)(3-chloropropyl)dimethoxysilane (11). The synthesis was carried out analo-

gously to that of **10**, starting from a solution of **9** (50.0 g, 252 mmol) in diethyl ether (100 mL) and a Grignard reagent prepared from 1,4-dibromobenzene (59.4 g, 252 mmol) and magnesium turnings (6.12 g, 252 mmol) in diethyl ether (200 mL) to give **11** in 47% yield as a colorless liquid (38.1 g, 118 mmol); bp 101 °C/0.06 mbar. ^{1}H NMR ($CDCl_3$): δ 0.90−1.01 (m, 2 H, SiCH_2C), 1.75−1.90 (m, 2 H, CCH_2C), 3.45−3.53 (m, 2 H, CCH_2Cl), 3.57 (s, 6 H, OCH_3), 7.43−7.57 (m, 4 H, C_6H_4-Br). ^{13}C NMR ($CDCl_3$): δ 9.8 (SiCH_2C), 26.2 (CCH_2C), 47.4 (CCH_2Cl), 50.7 (OCH_3), 125.4 (*C*-4, C_6H_4Br), 131.3 and 135.9 (*C*-2/*C*-3/*C*-5/*C*-6, C_6H_4Br), *C*-1 of the C_6H_4Br group not detected (probably overlapping with the signal at 131.3). ^{29}Si NMR ($CDCl_3$): δ −17.5. CI MS (positive ions): *m*/*z* 323 (<1%, $[M + H]^+$), 245 (100%, $[M - C_3H_6Cl]^+$). Anal. Calcd for $C_{11}H_{16}BrClO_2Si$: C, 40.82; H, 4.98. Found: C, 40.8; H, 5.1.

Preparation of (4-Bromophenyl)(chloromethyl)methoxyphenylsilane[39] (12). The synthesis was carried out analogously to that of **3**, starting from a solution of **10** (16.6 g, 56.2 mmol) in THF (50 mL) and a Grignard reagent prepared from bromobenzene (8.79 g, 56.0 mmol) and magnesium turnings (1.36 g, 56.0 mmol) in THF (60 mL) to give **12** in 73% yield as a colorless liquid (14.0 g, 41.0 mmol); bp 140−141 °C/0.1 mbar. ^{1}H NMR ($CDCl_3$): δ 3.25 (s, 2 H, SiCH_2Cl), 3.62 (s, 3 H, OCH_3), 7.32−7.65 (m, 9 H, C_6H_5, C_6H_4Br). ^{13}C NMR ($CDCl_3$): δ 26.7 (SiCH_2Cl), 52.1 (OCH_3), 125.8 (*C*-4, C_6H_4Br), 128.2, 131.3, 134.8, and 136.4 (*C*-2/*C*-3/*C*-5/*C*-6, C_6H_5; *C*-2/*C*-3/*C*-5/*C*-6 C_6H_4Br), 130.8 (*C*-4, C_6H_5), 131.4 (*C*-1, C_6H_5 or C_6H_4-Br), *C*-1 of the C_6H_4Br or C_6H_5 group not detected (probably overlapping with the signal at 134.8). ^{29}Si NMR ($CDCl_3$): δ −11.6. CI MS (positive ions): *m*/*z* 341 (5%, $[M + H]^+$), 185 (100%, $[M - C_6H_4Br]^+$). Anal. Calcd for $C_{14}H_{14}BrClOSi$: C, 49.21; H, 4.13. Found: C, 48.8; H, 4.0.

Preparation of (4-Bromophenyl)(3-chloropropyl)methoxyphenylsilane (13). The synthesis was carried out analogously to that of **3**, starting from a solution of **11** (38.0 g, 117 mmol) in THF (80 mL) and a Grignard reagent prepared from bromobenzene (18.4 g, 117 mmol) and magnesium turnings (2.84 g, 117 mmol) in THF (100 mL) to give **13** in 71% yield as a colorless liquid (30.9 g, 83.6 mmol); bp 147−148 °C/0.02 mbar. ^{1}H NMR ($CDCl_3$): δ 1.21−1.32 (m, 2 H, SiCH_2C), 1.79−1.94 (m, 2 H, CCH_2C), 3.46−3.56 (m, 2 H, CCH_2Cl), 3.52 (s, 3 H, OCH_3), 7.32−7.59 (m, 9 H, C_6H_5, C_6H_4Br). ^{13}C NMR ($CDCl_3$): δ 11.0 (SiCH_2C), 26.5 (CCH_2C), 47.6 (CCH_2Cl), 51.4 (OCH_3), 125.1 (*C*-4, C_6H_4Br), 133.0 and 133.5 (*C*-1, C_6H_5; *C*-1, C_6H_4Br), 128.1, 131.2, 134.5, and 136.2 (*C*-2/*C*-3/*C*-5/*C*-6, C_6H_5; *C*-2/*C*-3/*C*-5/*C*-6, C_6H_4Br), 130.3 (*C*-4, C_6H_5). ^{29}Si NMR ($CDCl_3$): δ −2.5. CI MS (positive ions): *m*/*z* 369 (<1%, $[M + H]^+$), 291 (100%, $[M - C_3H_6Cl]^+$). Anal. Calcd for $C_{16}H_{18}BrClOSi$: C, 51.97; H, 4.91. Found: C, 51.8; H, 4.9.

Preparation of (4-Bromophenyl)methoxy(morpholinomethyl)phenylsilane (14). The synthesis was carried out analogously to that of **5** (method A), starting from a solution of **12** (2.00 g, 5.85 mmol) and morpholine (1.53 g, 17.6 mmol) in toluene (20 mL) to give **14** in 67% yield as a colorless liquid (1.55 g, 3.95 mmol); bp 146 °C/0.07 mbar. ^{1}H NMR ($CDCl_3$): δ 2.34−2.53 (m, 6 H, SiCH_2N, CCH_2N), 3.49−3.68 (m, 4 H, CCH_2O), 3.55 (s, 3 H, OCH_3), 7.29−7.71 (m, 9 H, C_6H_5, C_6H_4-Br). ^{13}C NMR ($CDCl_3$): δ 47.8 (SiCH_2N), 51.6 (OCH_3), 57.3 (CCH_2N), 67.1 (CCH_2O), 125.1 (*C*-4, C_6H_4Br), 128.0, 131.1, 134.7, and 136.4 (*C*-2/*C*-3/*C*-5/*C*-6, C_6H_5; *C*-2/*C*-3/*C*-5/*C*-6, C_6H_4-Br), 130.2 (*C*-4, C_6H_5), 133.2 and 133.8 (*C*-1, C_6H_5; *C*-1, C_6H_4-Br). ^{29}Si NMR ($CDCl_3$): δ −8.9. EI MS: *m*/*z* 391 (1%, M^+), 100 (100%, $H_2C{=}NC_4H_8O^+$). Anal. Calcd for $C_{18}H_{22}BrNO_2Si$: C, 55.10; H, 5.65; N, 3.57. Found: C, 55.0; H, 5.7; N, 3.7.

Preparation of (4-Bromophenyl)methoxy(3-morpholinopropyl)phenylsilane (15). The synthesis was carried out analogously to that of **5** (method A, reaction time 3 days), starting from a solution of **13** (17.4 g, 47.1 mmol) and morpholine (12.3 g, 141 mmol) in toluene (30 mL) to give **15** in 51% yield as a colorless liquid (10.0 g, 23.8 mmol); bp 185 °C/0.08 mbar. ^{1}H NMR ($CDCl_3$): δ 1.01−1.20 (m, 2 H, SiCH_2C), 1.45−1.66 (m, 2 H, CCH_2C), 2.21−2.41 (m, 6 H, CCH_2N), 3.50 (s, 3 H, OCH_3), 3.58−3.69 (m, 4 H, CCH_2O), 7.25−7.61 (m, 9 H, C_6H_5, C_6H_4Br). ^{13}C NMR ($CDCl_3$): δ 10.7 (SiCH_2C), 19.8 (CCH_2C), 51.3 (OCH_3), 53.5 (NCH_2CO), 61.9 (CCCH_2N), 66.8 (CCH_2O), 124.8 (*C*-4, C_6H_4Br), 127.9, 131.0, 134.4, and 136.1 (*C*-2/*C*-3/*C*-5/*C*-6, C_6H_5; *C*-2/*C*-3/*C*-5/*C*-6, C_6H_4Br), 130.0 (*C*-4, C_6H_5), 133.3 and 133.8 (*C*-1, C_6H_5; *C*-1, C_6H_4Br). ^{29}Si NMR ($CDCl_3$): δ −1.7. EI MS: *m*/*z* 419 (<1%, M^+), 100 (100%, $H_2C{=}NC_4H_8O^+$). Anal. Calcd for $C_{20}H_{26}BrNO_2Si$: C, 57.14; H, 6.23; N, 3.33. Found: C, 57.1; H, 6.1; N, 3.2.

Preparation of (4-Bromophenyl)(chloromethyl)methoxymethylsilane (18). The synthesis was carried out analogously to that of **10**, starting from a solution of **16** (20.0 g, 129 mmol) in diethyl ether (60 mL) and a Grignard reagent prepared from 1,4-dibromobenzene (30.5 g, 129 mmol) and magnesium turnings (3.14 g, 129 mmol) in diethyl ether (100 mL) to give **18** in 49% yield as a colorless liquid (17.5 g, 62.6 mmol); bp 76 °C/0.07 mbar. ^{1}H NMR ($CDCl_3$): δ 0.50 (s, 3 H, SiCH_3), 2.94 (δ_A) and 3.01 (δ_B) ($^2J_{AB}$ = 14.0 Hz, 2 H, SiCH_2Cl), 3.54 (s, 3 H, OCH_3), 7.41−7.56 (m, 4 H, C_6H_4Br). ^{13}C NMR ($CDCl_3$): δ −5.6 (SiCH_3), 28.0 (SiCH_2Cl), 51.5 (OCH_3), 125.5 (*C*-4, C_6H_4Br), 131.3 and 135.4 (*C*-2/*C*-3/*C*-5/*C*-6, C_6H_4Br), 132.7 (*C*-1, C_6H_4Br). ^{29}Si NMR ($CDCl_3$): δ 1.1. EI MS: *m*/*z* 278 (<1%, M^+), 229 (100%, $M^+ - CH_2Cl$). Anal. Calcd for $C_9H_{12}BrClOSi$: C, 38.66; H, 4.33. Found: C, 38.5; H, 4.3.

Preparation of (4-Bromophenyl)(3-chloropropyl)methoxymethylsilane (19). The synthesis was carried out analogously to that of **10**, starting from a solution of **17** (25.0 g, 137 mmol) in diethyl ether (80 mL) and a Grignard reagent prepared from 1,4-dibromobenzene (32.3 g, 137 mmol) and magnesium turnings (3.33 g, 137 mmol) in diethyl ether (150 mL) to give **19** in 54% yield as a colorless liquid (22.6 g, 73.5 mmol); bp 98−99 °C/0.04 mbar. ^{1}H NMR ($CDCl_3$): δ 0.37 (s, 3 H, SiCH_3), 0.88−0.99 (m, 2 H, SiCH_2C), 1.73−1.89 (m, 2 H, CCH_2C), 3.41−3.53 (m, 2 H, CCH_2Cl), 3.44 (s, 3 H, OCH_3), 7.34−7.58 (m, 4 H, C_6H_4Br). ^{13}C NMR ($CDCl_3$): δ −4.4 (SiCH_3), 12.4 (SiCH_2C), 26.5 (CCH_2C), 47.5 (CCH_2Cl), 50.8 (OCH_3), 124.7 (*C*-4, C_6H_4Br), 131.1 and 135.1 (*C*-2/*C*-3/*C*-5/*C*-6, C_6H_4-Br), 134.8 (*C*-1, C_6H_4Br). ^{29}Si NMR ($CDCl_3$): δ 8.4. EI MS: *m*/*z* 291 (8%, $M^+ - CH_3$), 229 (100%, $M^+ - C_3H_6Cl$). Anal. Calcd for $C_{11}H_{16}BrClOSi$: C, 42.94; H, 5.24. Found: C, 43.0; H, 5.1.

Preparation of (4′-Fluorobiphenyl-4-yl)methoxy(3-morpholinopropyl)phenylsilane (20). A Grignard reagent was prepared from 1-bromo-4-fluorobenzene (1.31 g, 7.49 mmol) and magnesium turnings (182 mg, 7.49 mmol) in THF (4 mL) and then added at −20 °C to a stirred solution of freshly dried zinc bromide (1.69 g, 7.50 mmol) in THF (4 mL) (formation of a precipitate). After the reaction mixture was cooled to −50 °C, $PdCl_2$(dppf) (11.0 mg, 15.0 μmol) and **15** (630 mg, 1.50 mmol) were added one after another, and the resulting mixture was warmed to −10 °C over a period of 3 h and then stirred for 16 h at room temperature. The solvent was removed under reduced pressure, diethyl ether (2 mL) added to the residue, and the resulting precipitate filtered off. The solvent of the filtrate was removed under reduced pressure and the residue distilled in vacuo. *n*-Pentane (5 mL) was added to the distillate and the resulting precipitate removed by centrifugation. Finally, the solvent was removed under reduced pressure and the residue distilled in vacuo (Kugelrohr apparatus, 0.003 mbar, 245−250 °C; partial decomposition) to give **20** in 30% yield as a colorless oily liquid (199 mg, 457 μmol). ^{1}H NMR ($CDCl_3$): δ 1.10−1.23 (m, 2 H, SiCH_2C), 1.55−1.72 (m, 2 H, CCH_2C), 2.27−2.45 (m, 6 H, CCH_2N), 3.56 (s, 3 H, OCH_3), 3.63−3.73 (m, 4 H, CCH_2O), 7.05−7.70 (m, 13 H, C_6H_5, $C_{12}H_8F$). ^{13}C NMR ($CDCl_3$): δ 11.1 (SiCH_2C), 20.0 (CCH_2C), 51.4 (OCH_3), 53.7 (OCCH_2N), 62.1 (CCCH_2N), 67.0 (CCH_2O), 115.7 (d, $^2J_{CF}$ = 21.8 Hz, *C*-3′/*C*-5′, $C_{12}H_8F$), 126.5, 128.0, 130.0, 134.7, and 135.2 (*C*-2/*C*-3/*C*-5/*C*-6, C_6H_5; *C*-2/*C*-3/*C*-5/*C*-6, $C_{12}H_8F$; *C*-4, C_6H_5), 128.7 (d, $^3J_{CF}$ = 8.2 Hz, *C*-2′/*C*-6′, $C_{12}H_8F$), 133.3 and 134.5 (*C*-1, C_6H_5; *C*-4, $C_{12}H_8F$), 137.0 (d, $^4J_{CF}$ = 3.4 Hz, *C*-1′, $C_{12}H_8F$), 141.6 (*C*-1, $C_{12}H_8F$), 162.6 (d,

$^1J_{CF}$ = 247.1 Hz, *C*-4′, $C_{12}H_8F$). ^{19}F NMR ($CDCl_3$): δ −115.7. ^{29}Si NMR ($CDCl_3$): δ −1.8. CI MS (positive ions): *m*/*z* 436 (100%, $[M + H]^+$). Anal. Calcd for $C_{26}H_{30}FNO_2Si$: C, 71.69; H, 6.94; N, 3.22; F, 4.36. Found: C, 71.6; H, 6.9; N, 3.2; F 4.4.

General Procedure for the Preparation of 21−23 and 25. The respective silane (1.20 mmol: **5**, 484 mg; **6**, 500 mg; **24**, 511 mg) was added at room temperature to a solution of 1,2-dihydroxybenzene (264 mg, 2.40 mmol; to give **21**, **22**, and **25**) or glycolic acid (183 mg, 2.41 mmol; to give **23**) in acetonitrile (10 mL). The reaction mixture was shaken for 1 min and then kept undisturbed at room temperature for a period of 2 days (**21**−**23**; formation of a precipitate after ca. 15−45 min) or 5 days (**25**; formation of a precipitate after ca. 22 h). The crystalline solid was filtered off, washed with acetonitrile (3 × 5 mL), and then dried in vacuo (0.05 mbar, 20 °C, 6 h). Further product was obtained by concentration of the filtrate under reduced pressure (removal of ca. four-fifths of the solvent).

Data for Bis[benzene-1,2-diolato(2−)](morpholiniomethyl)silicate (21): yield 92% (381 mg, 1.10 mmol); colorless crystals; dec pt 225 °C. For solution NMR data (^{1}H, ^{13}C, ^{29}Si), see ref 28. Solid-state ^{29}Si VACP/MAS NMR: δ −87.3. APCI MS (negative ions): *m*/*z* 344 (4%, $[M(\text{zwitterion}) - H]^-$), 109 (100%, $C_6H_5O_2^-$). Anal. Calcd for $C_{17}H_{19}NO_5Si$: C, 59.11; H, 5.54; N, 4.05. Found: C, 59.1; H, 5.5; N, 4.3.

Data for Bis[benzene-1,2-diolato(2−)][(4-methylpiperazin-1-io)methyl]silicate (22): yield 78% (336 mg, 937 μmol); colorless crystals; dec pt 250 °C. ^{1}H NMR ([D$_6$]DMSO): δ 2.11−2.27 (m, 2 H, CC*H*$_2$N), 2.15 (s, 3 H, NC*H*$_3$), 2.63 (s, 2 H, SiC*H*$_2$N), 2.67−2.79, 2.82−2.98, and 3.15−3.28 (m, 6 H, CC*H*$_2$N), 6.50−6.69 (m, 8 H, C$_6$*H*$_4$O$_2$), 8.2 (broad s, 1 H, N*H*). ^{13}C NMR ([D$_6$]DMSO): δ 44.7 (N*C*H$_3$), 47.4 (Si*C*H$_2$N), 51.3 and 54.1 (*C*CH$_2$N), 110.5 (*C*-4/*C*-5, C$_6$H$_4$O$_2$), 118.2 (*C*-3/*C*-6, C$_6$H$_4$O$_2$), 149.4 (*C*-1/*C*-2, C$_6$H$_4$O$_2$). ^{29}Si NMR ([D$_6$]DMSO): δ −85.8. Solid-state ^{29}Si VACP/MAS NMR: δ −85.1. APCI MS (negative ions): *m*/*z* 357 (100%, $[M(\text{zwitterion}) - H]^-$). Anal. Calcd for $C_{18}H_{22}N_2O_4Si$: C, 60.31; H, 6.19; N, 7.81. Found: C, 60.3; H, 6.2; N, 7.8.

Data for Bis[glycolato(2−)-*O*^{1},*O*^{2}][(4-methylpiperazin-1-io)methyl]silicate (23): yield 81% (282 mg, 971 μmol); colorless crystals; mp 283 °C dec. ^{1}H NMR ([D$_6$]DMSO): δ 2.09−2.31 (m, 2 H, CC*H*$_2$N), 2.21 (s, 3 H, NC*H*$_3$), 2.45−2.67 (m, 2 H, SiC*H*$_2$N; overlapping with the [D$_5$]DMSO resonance signal), 2.68−3.18 and 3.43−3.65 (m, 6 H, CC*H*$_2$N), 3.92 (s, 4 H, OC*H*$_2$C), 8.1 (broad s, 1 H, N*H*). ^{13}C NMR ([D$_6$]DMSO): δ 44.8 (N*C*H$_3$), 47.3 (Si*C*H$_2$N), 51.5, 53.3, and 55.0 (C$_4$H$_8$N$_2$), 62.8 (O*C*H$_2$C), 173.9 (*C*═O). ^{29}Si NMR ([D$_6$]DMSO): δ −90.3. Solid-state ^{29}Si VACP/MAS NMR: δ −89.0. APCI MS (negative ions): *m*/*z* 289 (31%, $[M(\text{zwitterion}) - H]^-$), 75 (100%, $C_2H_3O_3^-$). Anal. Calcd for $C_{10}H_{18}N_2O_6Si$: C, 41.37; H, 6.25; N, 9.65. Found: C, 41.3; H, 6.2; N, 9.7.

Preparation of Methoxy{4-[(*E*)-2-(methoxycarbonyl)-vinyl]phenyl}(3-morpholinopropyl)phenylsilane (24). Silane **15** (1.20 g, 2.85 mmol), palladium(II) chloride (50.5 mg, 285 μmol), triphenylphosphane (150 mg, 572 μmol), methyl acrylate (270 mg, 3.14 mmol), and triethylamine (1.5 mL) were added one after another to DMF (1.5 mL), and the mixture was stirred for 20 h at 110 °C in a sealed flask. The volatile components were then removed in vacuo (0.1 mbar) at room temperature, and diethyl ether (10 mL) was added to the residue. The resulting precipitate was filtered off and washed with diethyl ether (3 × 5 mL). Filtrate and washing solutions were combined, and the solvent was removed under reduced pressure and the residue distilled in vacuo (Kugelrohr apparatus, 0.02 mbar, 245−250 °C; partial decomposition) to give **24** in 33% yield as a colorless oily liquid (401 mg, 942 μmol). ^{1}H NMR ($CDCl_3$): δ 1.10−1.21 (m, 2 H, SiC*H*$_2$C), 1.53−1.67 (m, 2 H, CC*H*$_2$C), 2.28−2.42 (m, 6 H, CC*H*$_2$N), 3.54 (s, 3 H, OC*H*$_3$), 3.64−3.71 (m, 4 H, CC*H*$_2$O), 3.81 (s, 3 H, OC*H*$_3$), 6.48 (d, $^3J_{HH}$ = 16.1 Hz, 1 H, C$_6$H$_4$CH═C*H*), 7.33−7.64 (m, 9 H, C$_6$*H*$_5$, C$_6$*H*$_4$), 7.70 (d, $^3J_{HH}$ = 16.1 Hz, 1 H, C$_6$H$_4$C*H*═CH). ^{13}C NMR ($CDCl_3$): δ 10.9 (Si*C*H$_2$C), 19.9 (C*C*H$_2$C), 51.4 (O*C*H$_3$), 51.8 (O*C*H$_3$), 53.7 (OC*C*H$_2$N), 62.0 (CC*C*H$_2$N), 66.9 (C*C*H$_2$O), 118.5 (C$_6$H$_4$C═*C*H), 127.4, 128.0, 134.6, and 135.2 (*C*-2/*C*-3/*C*-5/*C*-6, C$_6$H$_5$; *C*-2/*C*-3/*C*-5/*C*-6, C$_6$H$_4$), 130.1 (*C*-4, C$_6$H$_5$), 134.0 and 135.7 (*C*-1, C$_6$H$_5$; *C*-1, C$_6$H$_4$), 137.6 (*C*-4, C$_6$H$_4$), 144.7 (C$_6$H$_4$*C*H═C), 167.3 (*C*═O). ^{29}Si NMR ($CDCl_3$): δ −2.3. EI MS: *m*/*z* 425 (<1%, M^+), 410 (<1%, $M^+ - CH_3$), 394 (<1%, $M^+ - OCH_3$), 100 (100%, $H_2C{=}NC_4H_8O^+$). Anal. Calcd for $C_{24}H_{31}NO_4Si$: C, 67.73; H, 7.34; N, 3.29. Found: C, 67.5; H, 7.4; N, 3.2.

Data for Bis[benzene-1,2-diolato(2−)](3-morpholiniopropyl)silicate (25): yield 65% (291 mg, 779 μmol); colorless crystals; dec pt 230 °C. For solution NMR data (^{1}H, ^{13}C, ^{29}Si), see ref 28. APCI MS (negative ions): *m*/*z* 372 (4%, $[M(\text{zwitterion}) - H]^-$), 109 (100%, $C_6H_5O_2^-$). Anal. Calcd for $C_{19}H_{23}NO_5Si$: C, 61.10; H, 6.21; N, 3.75. Found: C, 60.8; H, 6.1; N, 3.9.

Preparation of the Piperazinomethyl-Substituted Polystyrene 27. A suspension of chloromethyl-substituted Merrifield resin (**26**, 5.00 g; substitution 1.08 mmol g^{-1}) in a solution of piperazine (4.65 g, 54.0 mmol) in DMF (50 mL) was mixed for 70 h at 50 °C in a Kugelrohr apparatus operating at ca. 15 rpm. The resulting resin was filtered off and washed successively with methanol (10 mL) and THF (10 mL). This washing procedure was repeated twice and the resin then dried in vacuo (0.01 mbar, 20 °C, 5 h). IR: ν 3340 cm^{-1} (w, NH). Anal. Found: Cl, <0.3%.

General Procedure for the Preparation of Resins 28 and 30−33. A suspension of **27** (1.00 g) in a solution of the respective silane (5.40 mmol: **4**, 1.91 g; **12**, 1.85 g; **13**, 2.00 g; **18**, 1.51 g; **19**, 1.66 g) and triethylamine (546 mg, 5.40 mmol) in THF (10 mL) was mixed for 20 h (**4**, **12**, **18**) or 9 days (**13**, **19**) at 50 °C in a Kugelrohr apparatus operating at ca. 15 rpm. The resulting resin was filtered off and washed successively with methanol (10 mL) and THF (10 mL). This washing procedure was repeated twice and the resin then dried in vacuo (0.01 mbar, 20 °C, 5 h). Solid-state ^{29}Si VACP/MAS NMR data: **28**, δ −9; **30**, δ −9; **31**, δ −2; **32**, δ 3; **33**, δ 8.

General Procedure for the Cleavage of Resins 28 and 30−33 with 1,2-Dihydroxybenzene. Formation of Resin 29 or 34.[43] A suspension of the respective resin (1.00 g) in a solution of 1,2-dihydroxybenzene (595 mg, 5.40 mmol) in acetonitrile (10 mL) was mixed for 20 h (**28**, **30**, **32**), 2 days (**31**), or 3 days (**33**) at 50 °C in a Kugelrohr apparatus operating at ca. 15 rpm. The resulting resin was filtered off and washed successively with methanol (10 mL) and THF (10 mL). This washing procedure was repeated twice and the resin then dried in vacuo (0.01 mbar, 20 °C, 5 h). Solid-state ^{29}Si VACP/MAS NMR data: **29**, δ −87; **34**, δ −74.

Preparation of Resin 35. A Grignard reagent was prepared from 1-bromo-4-fluorobenzene (945 mg, 5.40 mmol) and magnesium turnings (131 mg, 5.39 mmol) in THF (4 mL) and then added at −20 °C to a stirred solution of freshly dried zinc bromide (1.22 g, 5.40 mmol) in THF (10 mL) (formation of a precipitate). After the reaction mixture was cooled to −50 °C, $PdCl_2$(dppf) (7.90 mg, 10.8 μmol) and resin **32** (1.00 g) were added one after another, and the resulting mixture was warmed to −10 °C over a period of 3 h and then stirred for 16 h at room temperature. The resulting resin was filtered off and washed successively with methanol (10 mL) and THF (10 mL). This washing procedure was repeated twice and the resin then dried in vacuo (0.01 mbar, 20 °C, 5 h). Solid-state ^{29}Si VACP/MAS NMR: δ −2.

Preparation of Resin 36. The synthesis was carried out analogously to that of resin **35**, starting from a Grignard reagent prepared from 1-bromo-2-methoxybenzene (1.01 g,

(43) Cleavage of resin **33** did not proceed quantitatively: even after a reaction time of 3 days, the solid-state ^{29}Si VACP/MAS NMR spectrum of the resulting resin revealed resonance signals at −2, −11, and −57 ppm, along with a resonance signal at −74 ppm with relatively low intensity.

5.40 mmol) and magnesium turnings (131 mg, 5.39 mmol) in THF (5 mL), a solution of freshly dried zinc bromide (1.22 g, 5.40 mmol) in THF (10 mL), $PdCl_2$(dppf) (7.90 mg, 10.8 μmol), and resin **32** (1.00 g). Solid-state ^{29}Si VACP/MAS NMR: δ −1.

Preparation of Resin 37. A 1.6 M solution of *n*-butyllithium in *n*-hexane (3.38 mL, 5.40 mmol *n*-BuLi) was added at −78 °C within 2 min to a stirred solution of 2-bromothiophene (880 mg, 5.40 mmol) in THF (3 mL). After the reaction mixture was stirred for 15 min at −78 °C, a solution of freshly dried zinc bromide (1.22 g, 5.40 mmol) in THF (10 mL) was added within 5 min. The mixture was warmed to −50 °C, and $PdCl_2$(dppf) (7.90 mg, 10.8 μmol) and resin **32** (1.00 g) were added one after another. The suspension was warmed to room temperature over a period of 3 h and then stirred for 16 h. The resulting resin was filtered off and washed successively with methanol (10 mL) and THF (10 mL). This washing procedure was repeated twice and the resin then dried in vacuo (0.01 mbar, 20 °C, 5 h). Solid-state ^{29}Si VACP/MAS NMR: δ −3.

Preparation of Resin 38. Resin **32** (1.00 g), palladium(II) chloride (38.3 mg, 216 μmol), triphenylphosphane (227 mg, 865 μmol), methyl acrylate (465 mg, 5.40 mmol), and triethylamine (2.5 mL) were added one after another to DMF (15 mL), and the mixture was stirred for 7 h at 110 °C in a sealed flask. The resulting resin (still hot) was filtered off and washed successively with methanol (10 mL) and THF (10 mL). This washing procedure was repeated twice and the resin then dried in vacuo (0.01 mbar, 20 °C, 5 h). Solid-state ^{29}Si VACP/MAS NMR: δ −6.

Cleavage of Resins 35−38 with 1,2-Dihydroxybenzene. Formation of Resin 29. The cleavage reactions were carried out analogously to those of **28** and **30**−**33** (reaction times: **35**, 20 h; **36**−**38**, 2 days). Solid-state ^{29}Si VACP/MAS NMR: δ −87.

Isolation of the Target Molecules Obtained by Solid-Phase Synthesis. General Procedure. The filtrate and washing solutions obtained after the respective cleavage reaction (cleavage of resins **28**, **30**−**33**, and **35**−**38**; see above) were combined, and 1 M aqueous NaOH solution (20 mL) was added. The resulting mixture was extracted with diethyl ether (3 × 30 mL), and the combined organic layers were extracted with 1 M aqueous NaOH solution (2 × 20 mL) and then washed with water until the aqueous phase was neutral. Most of the solvent of the organic layer was removed by distillation at normal pressure (up to a boiling temperature of ca. 50 °C) and the rest of the solvent evaporated at room temperature to give the cleavage products biphenyl (from **28**), bromobenzene (from **30**−**33**), 4-fluorobiphenyl (from **35**), 2-methoxybiphenyl (from **36**), 2-phenylthiophene (from **37**), or methyl cinnamate (from **38**). The identities of these products were established by spectroscopic comparison with authentic samples. Yields, related to 1.00 g of (chloromethyl)-substituted Merrifield resin **27**: biphenyl, 70% (116 mg, 752 μmol), purity >99% (GC); bromobenzene (not isolated), see Table 5; 4-fluorobiphenyl, 57% (106 mg, 616 μmol), purity >99% (GC); 2-methoxybiphenyl, 53% (106 mg, 575 μmol), purity >99% (GC); 2-phenylthiophene, 35% (60.6 mg, 378 μmol), purity >99% (GC); methyl cinnamate, 87% (not isolated, yield determined by GC/MS studies).

Stability Tests of Resin 32. General Procedure. The respective reagent (540 μmol; see Table 6) was added to a suspension of resin **32** (100 mg) in THF (3 mL) and the resulting mixture then mixed for 20 h at 50 °C in a Kugelrohr apparatus operating at ca. 15 rpm. The resin was filtered off and washed successively with methanol (2 mL) and THF (2 mL). This washing procedure was repeated twice and the resin then dried in vacuo (0.01 mbar, 20 °C, 5 h). Subsequently, a solution of 1,2-dihydroxybenzene (59.5 mg, 540 μmol) in acetonitrile (3.0 mL) was added to the resin and the resulting mixture again mixed for 20 h at 50 °C in a Kugelrohr apparatus operating at ca. 15 rpm. The resin was filtered off and washed successively with methanol (2.0 mL) and THF (2.0 mL). This washing procedure was repeated twice and the resin then dried in vacuo (0.01 mbar, 20 °C, 5 h). Filtrate and washing solutions were combined, and the bromobenzene content of the resulting solution was quantified by HPLC experiments using 100 μL of this solution and 100 μL of a solution of anthracene (5.45 mg, 30.6 μmol) in THF (10.0 mL) as internal standard. The results of these studies are listed in Table 6.

Crystal Structure Analyses of 21−23. Suitable single crystals of **22** and **23** were obtained directly from the respective reaction mixtures (see General Procedure for the Preparation of **21**−**23** and **25**). Suitable single crystals of **21** were also obtained directly from the reaction mixture by using more acetonitrile (30 mL instead of 10 mL) and a longer crystallization time (7 days instead of 2 days) compared to the General Procedure. The crystals were mounted in inert oil (RS 3000, Riedel-de Haën) on a glass fiber and then transferred to the cold nitrogen gas stream of the diffractometer (Stoe IPDS; graphite-monochromated Mo Kα radiation (λ = 0.710 73 Å)). All structures were solved by direct methods.[44] All non-hydrogen atoms were refined anisotropically.[45] For **23** a riding model was employed in the refinement of the CH hydrogen atom positions; for **21** and **22** the CH hydrogen atoms were localized in difference Fourier syntheses and refined freely. The NH hydrogen atoms of **21**−**23** were localized in difference Fourier syntheses and refined freely.

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Supporting Information Available: Tables of atomic coordinates, additional interatomic distances and angles, and anisotropic thermal parameters for **21**−**23**. This material is available free of charge via the Internet at http://pubs.acs.org.

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(44) Sheldrick, G. M. SHELXS-96; University of Göttingen, Göttingen, Germany, 1996. Sheldrick, G. M. *Acta Crystallogr., Sect. A* **1990**, *46*, 467−473.

(45) Sheldrick, G. M. SHELXL-96; University of Göttingen, Göttingen, Germany, 1996.