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Heterocycles

Anionic Access to Silylated and Germylated Binuclear Heterocycles

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Abstract: A simple access to silylated and germylated binuclear heterocycles, based on an original anionic rearrangement, is described. A set of electron-rich and electron-poor silylated aromatic and heteroaromatic substrates were tested to understand the mechanism and the factors controlling this rearrangement, in particular its regioselectivity. This parameter was shown to follow the rules proposed before from a few examples. Then, the effect of the substituents borne by the silicon itself, in particular the selectivity of the ligand transfer, was studied. Additionally, this chemistry was extended to germylated substrates. A hypervalent germanium species, comparable to the putative intermediate proposed with silicon, seems to be involved. However, a pathway implicating the elimination of $LiCH_2Cl$ was observed for the first time with this element, leading to unexpected products of the benzo-oxa (or benzo-aza) germoltype.

Introduction

Swapping the carbon and silicon atoms is known to alter significantly the physicochemical properties of organic compounds and, when it comes to molecules of biological interest, of the corresponding absorption, distribution, metabolism, excretion, and toxicity (ADME-Tox).[1] These differences are partly related to the size of the silicon atom, which is larger than the carbon atom (with a covalent radius of 1.17 vs. 0.77 Å for carbon) and makes longer covalent bonds with other elements (the C–Si bond is 1.87 vs. 1.54 Å for an average C–C bond). This characteristic triggers significant differences in the molecular geometry and thus modifies the efficiency and/or selectivity and the rate of metabolism. Also, the lipophilicity of silylated analogues is superior to that of the all-carbon molecule and generally favors the penetration of the drug within the cell membrane in vivo. These phenomena explain that the silicon atom is generally regarded as a bioisostere of the carbon atom.[2–3]

All these reasons explain that the systematic exploration of the metalloid effect in drugs is the object of an increasing interest in the recent years.[4] Furthermore, this isosterism was also applied to other fields than in medicinal chemistry. For example in odorants design, replacing a carbon atom by a silicon is also a new strategy to create unique signatures in perfumery.[5] More recently, the carbon atom substitution was pushed further and the next crystallogen element, germanium, attracted attention. The C/Ge swap that goes with a further increase of the covalent radius, lipophilicity, and electropositivity was rapidly applied to bioactive compounds[6–7] as well as perfume ingredients or in the design of fungicides.[8]

The group of Tacke has been one of the main contributors in the field and this laboratory published among the most remarkable examples (Figure 1). For instance, a C/Si substitution

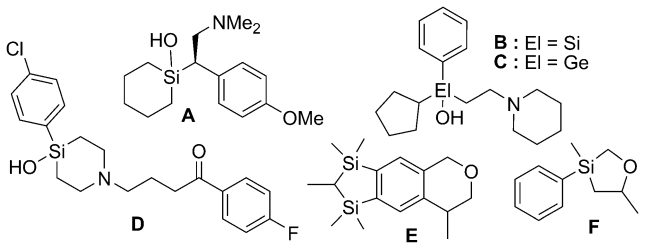

Figure 1. A few examples of C/Si or C/Ge switch in drugs or fragrance.

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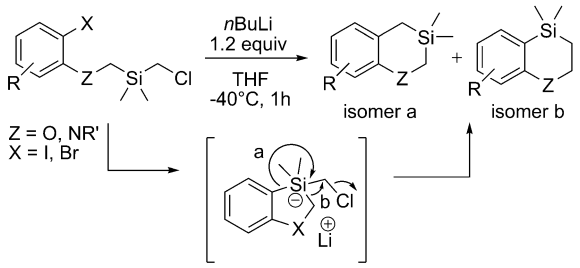
in venlafaxin, an antidepressant marketed for several years (Effexor, Efexor, and Trevilor), affords (*R*)-sila-venlafaxin **A**, which exhibits antiemetic properties.[9] The case of the sila- and germa-analogous derivatives of the muscarinic antagonist cycrimines **B** and **C**, respectively, which display a higher affinity than the corresponding alcohols, is also worth noting.[10] A spectacular example is given with the silylated analogue of haloperidol: A drug prescribed since the 1950s for the treatment of neuropsychiatric disorders such as schizophrenia, that is, sila-haloperidol **D**. This compound is not only as powerful as its carbon analogue (with an inhibition constant of 0.85 nM for the hD2 receptors against 4.0 nM in the case of haloperidol), but has also a very different metabolic fate in vivo.[11] Note that silicon-containing odorants like sila-rhubafuran **E** and disila-galaxolide **F** have been synthetized very recently in the same laboratory, introducing enthusing possibilities of development in the field.[12]

Undoubtedly, the relatively limited number of methodological tools available for the synthesis of heterocycles incorporating elements such as Si or Ge, still hampers these researches.[13] We have recently described a new rearrangement (termed sila-Matteson) that gives access to two regioisomeric silylated heterocycles of the dihydrobenzooxa- (or aza-) silines family. The electronic character of the fused aromatic ring was shown to govern the ratio between the regioisomers and a mechanism involving a pentaorganosilicate species was evidenced (Scheme 1).[14] This preliminary study was conducted on dimethyl-substituted silicon tethers borne by several phenol and aniline derivatives. We describe in this paper the generalization of this chemistry to a series of new silylated substrates, as well as its extension toward the germylated ones.



Scheme 1. Sila-Matteson rearrangement through a hypervalent-silicon species.

Results and Discussion

We first decided to check the robustness of our methodology toward various aromatic derivatives. In our original communication, we only varied the substituents R (Scheme 1) borne by the phenyl nucleus. To extend the scope of this transformation, we tried to apply it to new substrates, in particular heterocyclic ones (Table 1). The halogen–lithium exchange and subsequent nucleophilic substitution was performed at −40 °C using *n*-butyllithium in tetrahydrofuran.[15] The results of this methodological widening are satisfactory since yields remain good-to-excellent, except in the case of the 2-aminopyridine derivatives **12** and **13** for which purification problems were encountered (entries 12 and 13, Table 1). The **a**/**b** regioselectivity follows the trends underlined in our original paper, that is, the electron-deficient aromatic moieties favor the **a** isomers whereas electron-rich substituents lead to the **b** isomers. The pyridine derivatives follow this rule particularly well: in these cases, the single isomers **a** are obtained (entries 8–13, Table 1). In contrast, the *o*-bromothiophenol derivative **5** leads only to isomer **b** (entry 5, Table 1), even with derivative **6** featuring a fluorine atom in position 4 (entry 6, Table 1).

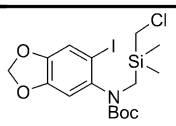
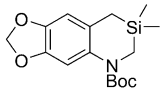
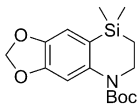
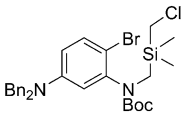
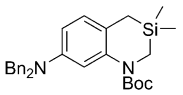
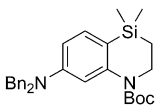
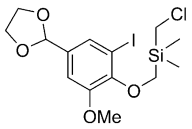
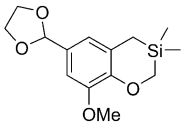
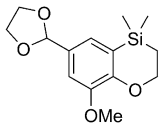
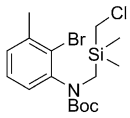
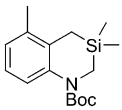
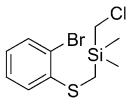
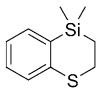
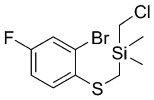
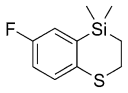
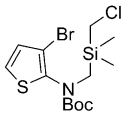
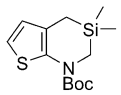
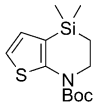
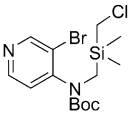
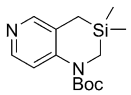
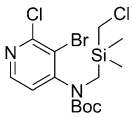
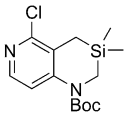
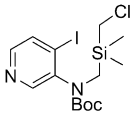
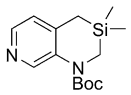
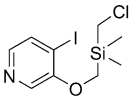
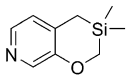
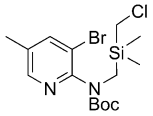
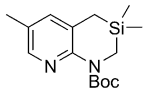
On the other hand, a strong *ortho*-substituent effect is observed in the case of the 2-bromo-3-methyl-aniline derivative **4**, which provides exclusively the **a** isomer (entry 4, Table 1), whereas the 2-bromo-5-methyl analogue led to a 37:63 ratio between the **a** and **b** isomers.[14] Note that the construction of a [3.4.0] silylated bicyclic skeleton is also possible by this route, as demonstrated in the case of thiophene **7** (entry 7, Table 1).

The striking selectivity observed with the pyridine derivatives led us to check that our mechanistic hypothesis, that is, the formation of a pentacoordinated silicon intermediate (Scheme 1), still applied in these cases. We thus prepared the azasylolpyridine **27** by adding 2 equiv of *n*-BuLi on protected 2-bromo-3-amino-pyridine and quenching the resulting dianion with $Me_2(CH_2Cl)SiCl$. Compound **27** features a silylated five-membered ring which, after reaction with the lithium carbenoid generated from chloroiodomethane, provided the dihydropyrido-azasiline **21** in 56% yield, most probably through the same siliconate intermediate (Scheme 2).

To expand again the scope of this transformation, we decided to vary the silicon substituents and check if we could fine-tune the selective transfer of this rearrangement. In addition, the phenyl appendage on the silicon constitutes a supplementary asset since the Si–Ph link can be easily replaced by a variety of other elements. We thus prepared a series of substrates including phenol, aniline, and 4-aminopyridine derivatives bearing a dimethyl-, methyl/phenyl-, or diphenylchloromethylsilyl tether (Table 2). The precursors **28**–**35** were easily obtained from the corresponding aromatics and bis(chloromethyl)dimethylsilane, bis(chloromethyl)methylphenylsilane, or bis-(chloromethyl)diphenylsilane, which are either commercially available or were synthesized from bis(chloromethyl)-(methyl)chlorosilane and dichlorodiphenylsilane in almost quantitative yields.[16] Next, the halogen–lithium exchange followed by the rearrangement was performed in THF at −40 °C for 1 h using *n*-BuLi.

In these standard conditions, the isomers **a** and/or **b** were recovered in good yields for the $SiMe_2$ and SiMePh derivatives (Table 2). Interestingly, substituting a methyl by a phenyl group favored the formation of the **b** isomer in the case of phenyl ethers **28** and **29** and afforded exclusively the **b** isomer in the case of the aniline derivative **32** (compare entries 1/2 and 4/5, Table 2). These results suggest that, in addition to the electronic control exerted by the aromatic nucleus, steric effects imposed by the other silicon substituents influence the fate of the pentavalent intermediate.[17] When it comes to the 4-aminopyridine derivatives **8** and **34**, this effect is not observed

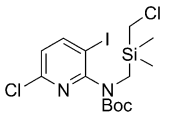
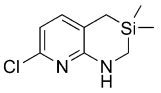
Table 1. Extension of the sila-Matteson rearrangement to various substrates.

Entry	Starting material		Yield [%][a]	Product(s)		a/b[b]
1		**1**	94[c]			**14a/14b** 50:50
2		**2**	70[c]			**15a/15b** 10:90
3		**3**	85			**16a/16b** 75:25
4		**4**	87[c]		–	**17a/17b** 100:0[d]
5		**5**	99	–		**18a/18b** 0:100
6		**6**	87[c]	–		**19a/19b** 0:100
7		**7**	67			**20a/20b** 45:55
8		**8**	78[c]		–	**21a/21b** 100:0
9		**9**	43		–	**22a/22b** 100:0
10		**10**	99[c]		–	**23a/23b** 100:0
11		**11**	99[c]		–	**24a/24b** 100:0
12		**12**	18[c,e]		–	**25a/25b** 100:0

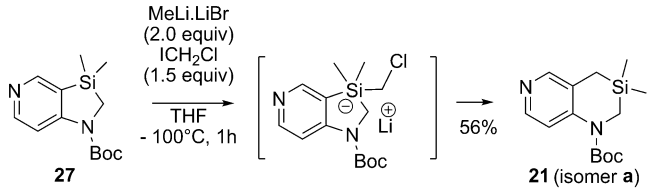
anymore, probably because the prime electron-deficient character of the pyridine moiety drives the rearrangement toward the **a** isomer, as noted before with other electron-withdrawing phenyl substituents.[14] Note that the results in entries 7 and 8 (Table 2) demonstrate that the sila-Matteson rearrangement applies equally well to pyridinic substrates, extending substantially its interest in heterocyclic chemistry.

In the case of the $SiPh_2$ derivatives **30**, **33**, and **35**, we observed for the first time the formation of a five-membered silylated heterocycle bearing a phenyl and a benzyl group on the silicon atom. This isomer results probably from the migration of a phenyl from the pentavalent species toward the chloromethyl appendage, further supporting the hypothesis of the formation of this hypervalent intermediate (Scheme 3). Isomer **c** is the major product in the case of the aniline **33** and pyridine **35**. It is known that the migratory aptitude of a phenyl group is superior to that of a methyl;[18] nevertheless, this rearrangement was not observed in the case of the SiMePh substrates **29**, **32**, and **34**. Interpreting these results requires caution since the pentavalent intermediate is generally believed to adopt a trigonal-bipyramidal conformation subjected to the Berry pseudorotation.[19] It is known, at least on comparable trigonal-bipyramidal tetraoxyphosphorans,[20] or pentaorganosilicates[17] that the phenyl groups tend to occupy the apical position (apicophilicity). We can thus suggest that **30**, **33**, and **35** evolve through a pentavalent species similar to that pictured on Scheme 3 in which the two phenyls are axial and the chloromethyl in the equatorial plane.[21] This situation seems ideal for the Ph→Cl substitution

Table 1. (Continued)

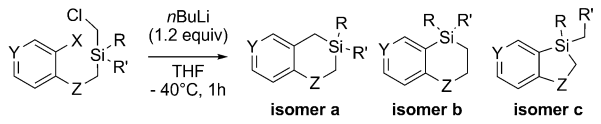
Entry	Starting material		Yield [%][a]	Product(s)		a/b[b]
13		**13**	39[c,e]		–	**26a**/**26b** 100:0

[a] Total yield for the two isomers after purification. [b] **a**/**b** determined in the crude reaction mixture by ^{1}H NMR spectroscopy. [c] *t*BuLi was employed instead of *n*-BuLi (see Ref. [15]). [d] A small amount (7%) of isomer **d** (see below and in the Supporting Information) was obtained in this case. [e] The reaction was quenched with acetic acid to avoid a sila-ring fission into silanol.



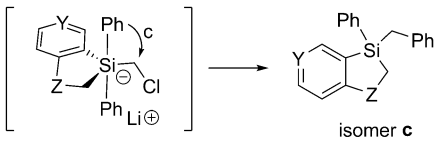
Scheme 2. Ring expansion supporting a mechanism involving a hypervalent siliconate.

Table 2. Effect of the silicon substituents on the selectivity of the cyclization.



Entry	Starting material	Z[c]	Y	R	R′	Product (**a**/**b**/**c**)[a]	Yield [%][b]
1	**28**	O	CH	Me	Me	**36a**/**36b**/**36c** 60:40:0	85
2	**29**	O	CH	Ph	Me	**37a**/**37b**/**37c** 24:76:0	70
3	**30**	O	CH	Ph	Ph	**38a**/**38b**/**38c** 20:50:30	74
4	**31**	N-Boc	CH	Me	Me	**39a**/**39b**/**39c** 45:55:0	84
5	**32**	N-Boc	CH	Ph	Me	**40a**/**40b**/**40c** 0:100:0	80
6	**33**	N-Boc	CH	Ph	Ph	**41a**/**41b**/**41c** 0:35:65	78
7	**8**	N-Boc	N	Me	Me	**21a**/**21b**/**21c** 100:0:0	63
8	**34**	N-Boc	N	Ph	Me	**42a**/**42b**/**42c** 100:0:0	77
9	**35**	N-Boc	N	Ph	Ph	**43a**/**43b**/**43c** 25:0:75	51

[a] Ratios **a**/**b**/**c** were determined in the crude reaction mixture by ^{1}H NMR spectroscopy. [b] Total yield for the three isomers after purification. [c] Boc = *tert*-butoxycarbonyl.



Scheme 3. Putative mechanism for the formation of isomer **c**.

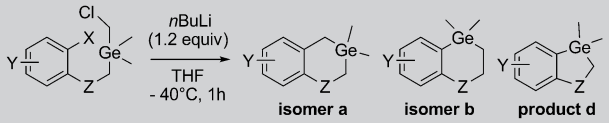
to take place, at least if the pseudorotation is the kinetically determining step.[22]

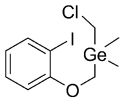
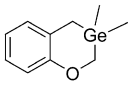
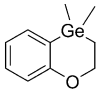
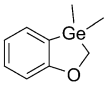
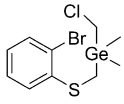
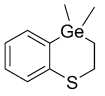
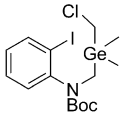
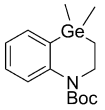
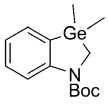
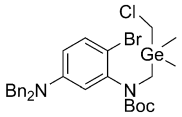
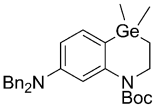
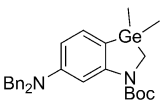
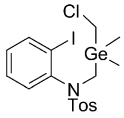
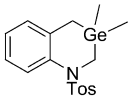
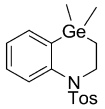
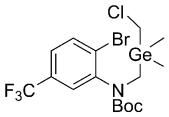
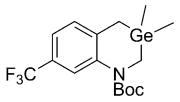
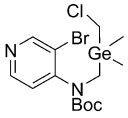
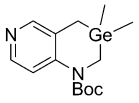
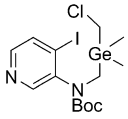
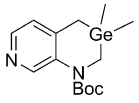
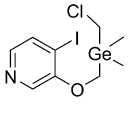
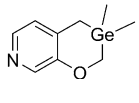
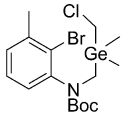
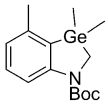
A more drastic extension of this methodology consisted in considering the germylated analogues. The starting materials were prepared by treating the corresponding (thio)phenols, anilines and pyridines with bis(-chloromethyl)dimethylgermane. They were then subjected to the above conditions of cyclization (Table 3).

The results show that the same chemistry applies to the germylated substrates and follow similar patterns, leading to the formation of binuclear heterocycles incorporating a Ge nucleus. In most cases, the two [4:4:0] bicyclic **a** and **b** isomers are obtained, suggesting that the reaction goes through a pentacoordinated germanium entity probably comparable to the putative intermediate proposed in the case of silicon. Note that in entries 1, 3, 4, and 10 (Table 3) a new family of derivatives **d** is now observed. Their structure, based on a [4:3:0] bicyclic skeleton, is of the benzo-oxa (or benzo-aza) germol-type. These products can result from the release of a $LiCH_2Cl$ carbenoid of the same pentavalent intermediate (Scheme 4). This reaction, which affords compounds **54d**, **56d**, **57d**, was not observed with silicon. The difference between the radii of Si (111 pm) and Ge (125 pm) can help to rationalize this observation: The elimination rate of $LiCH_2Cl$ would increase for the largest element with respect to that of the intramolecular substitution. Interestingly, compound **53** leads exclusively to **63d**, suggesting that the *ortho*-methyl group is also likely to slow down the chlorine substitution. This effect, which was glimpsed in the silylated series (see Table 1, entry 4, footnote [d]) is synergetic to the Ge influence and can explain that only the **d** product was obtained in this case.

In fine accord with the results obtained for the silicon derivatives **5** and **6**, germanyl thioether **45** provides exclusively the **b** isomer, as with all electron-rich aromatic substrates. Indeed, the rearrangement of **49** led exclusively to isomer **a** (entry 6, Table 3), whereas the silicon analogue allowed the formation of a 86:14 ratio between the **a** and **b** isomers. In contrast, a 22:78 mixture of **a** and **b** was obtained when reacting **48** (entry 5, Table 3), whereas the cyclization of the silicon analogue provided the sole isomer **b**. It is tempting to correlate these results to the relative electronegativity of silicon (1.90) and germanium (2.01). Indeed, a germylated appendage decreases the electron density on the aromatic ring more than its silylated analogue, favoring the exclusive heterolytic cleavage of the Ar–Ge bond of the pentavalent species and thus the selective formation of isomer **a** (entry 6, Table 3). Similarly, the electron-deficient pyridine rings trigger a rearrangement in favor of the sole **a** isomer, regardless of the nature of the substituent (Si/Ge), the position of the nitrogen or the heteroelement in the fused saturated heterocycle (entries 7 to 9, Table 3).

Table 3. Extension of the rearrangement to germylated substrates using *n*- or *t*BuLi.

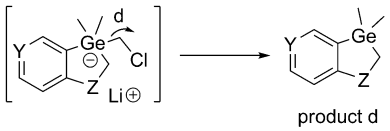


Entry	Starting material	Yield [%][a]	Product(s)			a/b/d[b]
1		**44** 82				**54a/54b/54d** 25:6:69
2		**45** 99	–		–	**55a/55b/55d** 0:100:0
3		**46** 57	–			**56a/56b/56d** 0:54:46
4		**47** 89[c]	–			**57a/57b/57d** 0:83:17
5		**48** 62			–	**58a/58b/58d** 15:85:0
6		**49** 55		–	–	**59a/59b/59d** 100:0:0
7		**50** 75		–	–	**60a/60b/60d** 100:0:0
8		**51** 93[c]		–	–	**61a/61b/61d** 100:0:0
9		**52** 84[c]		–	–	**62a/62b/62d** 100:0:0
10		**53** 92[c]	–	–		**63a/63b/63d** 0:0:100

[a] Total yield for the three isomers after purification. [b] Ratios **a**/**b**/**d** were determined in the crude reaction mixture by ^{1}H NMR spectroscopy. [c] *t*BuLi was employed instead of *n*-BuLi (see Ref. [15]).

Conclusion

This manuscript reports an access to a variety of silylated and germylated binuclear heterocycles, based on an original anionic rearrangement. We show that the direct correlation between the electron density on the aromatic ring and the proportion of the **a** and **b** isomers we had noticed in a recent note applies to a large number of substrates, including heterocyclic ones. This latter family of substrates affords a series of heteroaromatic and silylated binuclear scaffolds of significant interest in medicinal chemistry but also potentially important for the discovery of new analogues of classical fragrances. In a second phase of the study, we demonstrate that replacing the two methyl borne by the silicon tether with one or two phenyl leads to different mixtures of the known **a** and **b** isomers, and to a never observed isomer **c** when a $SiPh_2$ link is employed. It is very likely that isomer **c** results from the migration of one of the two phenyl nuclei. The formation of this new family of compounds buttresses the hypothesis of a common pentavalent silicon precursor for all the isomers, the chemoselectivity of the rearrangement obviously depending on the nature of the substituents of the silicon. Pleasingly enough, this chemistry extends efficiently to the germylated analogues. The rearrangement follows a pattern similar to that of silicon, suggesting that a comparable anionic hypervalent germanium species is involved. Moreover, benzo-oxa and benzo-azagermol-type products (product **d**) were also recovered in several cases, suggesting that an additional pathway implicating the elimination of $LiCH_2Cl$ occurs with Ge, a route marginally detected in the case of Si. This Si–Ge swap effect is reinforced by



Scheme 4. Putative mechanism for the formation of product **d**.

an *ortho* substituent, a phenomenon that could be employed to control the chemoselectivity using an easily removable *ortho* substituent.

In conclusion, this paper opens an access to new binuclear heterocycles incorporating a silicon or germanium atom in one of the rings. A stimulating next step will consist in including these scaffolds into more elaborated bioactive molecules and measure their impact on the reactivity, stability, and ADME profiles. Thus, an analogue of Motesanib (Figure 2), a drug-candidate acting as antagonist of a vascular endothelial growth factor receptors (VEGFRs), platelet-derived growth factor (PDGFR), and dedicated to the treatment of solid tumors, is currently targeted. This work is in progress and the results will be reported in due course.

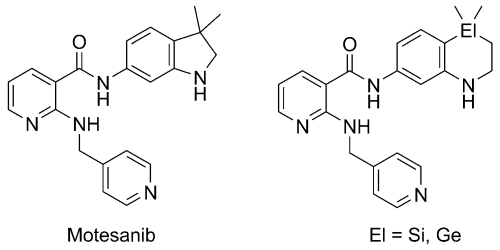


Figure 2. Structure of Motesanib and of a silylated/germylated analogue target.

Experimental Section

General procedures

GC analysis was carried out using a 24 m HP-methyl silicon capillary column. Mass spectra were recorded with a quadrupolar MS instrument coupled to a gas chromatograph. Elemental analyses were performed in house on standard equipment. Column chromatographies were run on standard silica gel (230–400 mesh). ^{1}H NMR spectra were recorded in $CDCl_3$ or C_6D_6 at 300 MHz, and ^{13}C NMR spectra were recorded at 75 MHz; chemical shift (δ) are given in parts per million (ppm) and the coupling constants (J) in hertz. IR spectra were recorded by transmission on an IRFT spectrometer.

General procedure for the anionic rearrangement: A solution of *n*-BuLi in hexane (1.6 M, 1.2 equiv) or at −78 °C a solution of *t*BuLi in hexane (1.7 M, 2.4 equiv) was added dropwise at −40 °C into a solution of halogenoaryl precursor (1.0 equiv) in anhydrous THF (10 mL mmol^{-1}). After 1 h, the reaction mixture was quenched at −40 °C or at −78 °C with a saturated aqueous solution of ammonium chloride, allowed to warm up to room temperature and extracted with diethyl ether. The resulting organic phase was then dried over anhydrous sodium sulfate and concentrated under reduced pressure. The crude mixture was finally purified by flash chromatography on silica gel using the appropriate mixture of eluents.

Compound 14a: ^{1}H NMR (300 MHz, $CDCl_3$): δ = 6.63 (br s, 1H), 6.56 (s, 1H), 5.90 (s, 2H), 3.00 (br s, 2H), 1.82 (s, 2H), 1.43 (s, 9H), 0.10 ppm (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 155.0, 145.3, 144.9, 134.2, 127.4, 109.0, 108.2, 100.9, 79.9, 35.1, 28.4 (3C), 19.0, −2.8 ppm (2C); MS (CI, isobutane): *m/z* (%): 322 (20) [$M+H^+$], 266, (100) [$M+H^+-t$Bu], 222 (20) [$M+H^+-$Boc].

Compound 14b: ^{1}H NMR (300 MHz, $CDCl_3$): δ = 6.84 (br s, 1H), 6.78 (s, 1H), 5.92 (s, 2H), 3.76–3.72 (m, 2H), 1.47 (s, 9H), 1.13–1.09 (m, 2H), 0.22 ppm (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 154.2, 148.1, 144.9, 143.3, 123.0, 111.0, 108.0, 100.9, 80.2, 45.4, 28.4 (3C), 13.6, −1.1 ppm (2C).

***tert*-Butyl 7-(dibenzylamino)-3,3-dimethyl-3,4-dihydrobenzo[*e*]-[1,3]azasiline-1(2*H*)-carboxylate (15a)**: ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.37–7.19 (m, 11H), 6.89 (d, J = 2.2 Hz, 1H), 6.52 (dd, J = 8.1, 2.2 Hz, 1H), 4.60 (s, 4H), 3.03 (br s, 2H), 1.82 (s, 2H), 1.35 (s, 9H), 0.12 ppm (s, 6H); ^{13}C NMR (50 MHz, $CDCl_3$): δ = 154.9, 147.4, 141.6, 138.7 (2C), 130.3, 128.6 (4C), 126.8 (2C), 126.7 (4C), 122.1, 111.9, 110.8, 79.5, 54.2 (2C), 35.5, 28.4 (3C), 17.4, −2.6 ppm (2C); IR (neat): $\tilde{\nu}$ = 2934, 1688, 1597, 1148, 727 cm^{-1}; HRMS (ESI+): *m/z* calcd for $C_{29}H_{37}N_2O_2Si$: 473.2624; found: 473.2623.

***tert*-Butyl 7-(dibenzylamino)-4,4-dimethyl-3,4-dihydrobenzo[*b*]-[1,4]azasiline-1(2*H*)-carboxylate (15b)**: M.p.: 124 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.36–7.19 (m, 11H), 6.77 (d, J = 1.9 Hz, 1H), 6.59 (dd, J = 8.4, 1.9 Hz, 1H), 4.65 (s, 4H), 3.79–3.75 (m, 2H), 1.41 (s, 9H), 1.13–1.09 (m, 2H), 0.22 ppm (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 154.0, 150.0, 149.9, 138.3 (2C), 134.3, 128.6 (4C), 126.8 (2C), 126.5 (4C), 116.8, 109.9, 109.5, 79.8, 53.7 (2C), 45.2, 28.3 (3C), 13.7, −0.9 ppm (2C); IR (neat) : $\tilde{\nu}$ = 2928, 1691, 1378, 1139, 700 cm^{-1}; HRMS (ESI+): *m/z* calcd for $C_{29}H_{37}N_2O_2Si$: 473.2624; found: 473.2617.

6-(1,3-Dioxolan-2-yl)-8-methoxy-3,3-dimethyl-3,4-dihydro-2*H*-benzo[e][1,3]oxasiline (16a): ^{1}H NMR (300 MHz, $CDCl_3$): δ = 6.84 (d, J = 1.8 Hz, 1H), 6.82 (d, J = 1.8 Hz, 1H), 5.70 (s, 1H), 4.17–4.13 (m, 2H), 4.05–4.00 (m, 2H), 3.86 (s, 3H), 3.85 (s, 2H), 2.00 (s, 2H), 0.16 ppm (s, 6H).

8-Methoxy-3,3-dimethyl-3,4-dihydro-2*H*-benzo[*e*][1,3]oxasiline-6-carbaldehyde: (after acetal deprotection): ^{1}H NMR (300 MHz, $CDCl_3$): δ = 9.80 (s, 1H), 7.22 (d, J = 1.8 Hz, 1H), 7.21 (d, J = 1.8 Hz, 1H), 3.95 (s, 2H), 3.89 (s, 3H), 2.08 (s, 2H), 0.19 ppm (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 191.4, 152.6, 151.3, 130.3, 129.5, 127.4, 107.5, 63.7, 56.2, 16.1, −3.7 ppm (2C); MS (EI, 70 eV): *m/z* (%) : 236 (100) [M^+], 221, (64) [M^+-Me), 205 (36) [$M-$OMe].

6-(1,3-Dioxolan-2-yl)-8-methoxy-4,4-dimethyl-3,4-dihydro-2*H*-benzo[b][1,4]oxasiline (16b): ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.02 (d, J = 1.8 Hz, 1H), 6.98 (d, J = 1.8 Hz, 1H), 5.73 (s, 1H), 4.42–4.38 (m, 2H), 4.17–4.13 (m, 2H), 4.05–4.00 (m, 2H), 3.87 (s, 3H), 1.16–1.12 (m, 2H), 0.28 ppm (s, 6H).

8-Methoxy-4,4-dimethyl-3,4-dihydro-2*H*-ben-zo[*b*][1,4]oxasiline-6-carbaldehyde: (after acetal deprotection): ^{1}H NMR (300 MHz, $CDCl_3$): δ = 9.84 (s, 1H), 7.45 (d, J = 1.8 Hz, 1H), 7.35 (d, J = 1.8 Hz, 1H), 4.46–4.50 (m, 2H), 3.91 (s, 3H), 1.20–1.16 (m, 2H), 0.33 ppm (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 191.3, 158.9, 149.4, 131.9, 130.2, 121.8, 109.8, 67.6, 56.0, 12.9, −1.7 ppm (2C); MS (EI, 70 eV): *m/z* (%): 236 (12) [M^+], 208 (100) [M^+-CO].

***tert*-Butyl 3,3,5-trimethyl-3,4-dihydrobenzo[*e*][1,3]azasiline-1(2*H*)-carboxylate (17a)**: ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.05–6.99 (m, 3H), 3.08 (br s, 2H), 2.31 (s, 3H), 1.93 (br s, 2H), 1.47 (s, 9H), 0.13 ppm (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 154.9, 140.8, 138.8, 132.6, 127.0, 124.9, 124.1, 79.4, 34.5, 28.2 (3C), 20.4, 14.3, −3.0 ppm

(2C); $\tilde{\nu}$ = 2952, 2925, 2865, 1672, 1143, 843 cm^{-1}; HRMS (ESI+): *m/z* calcd for $C_{16}H_{26}NO_2Si$: 292.1733; found: 292.1735.

4,4-Dimethyl-3,4-dihydro-2*H*-benzo[*b*][1,4]thiasiline (18 b): ^1H NMR (300 MHz, $CDCl_3$): δ = 7.43–7.40 (m, 1H), 7.25–7.22 (m, 1H), 7.18 ($t_{ap.}$d, *J* = 7.8 Hz, 1.5 Hz, 1H), 7.11 ($t_{ap.}$d, *J* = 7.2 Hz, 1.5 Hz, 1H), 3.08–3.03 (m, 2H), 1.34–1.29 (m, 2H), 0.28 ppm (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 145.1, 135.1, 135.0, 129.1, 128.1, 124.8, 28.6, 15.4, −1.0 ppm (2C); IR (neat): $\tilde{\nu}$ = 2953; 2922, 2886, 1418, 12498, 743 cm^{-1}; MS (EI, 70 eV): *m/z* (%): 194 (60) [M^+], 166 (100), 151 (84).

6-Fluoro-4,4-dimethyl-3,4-dihydro-2*H*-benzo[*b*][1,4]thiasiline (19 b): ^1H NMR (300 MHz, $CDCl_3$): δ = 7.21 (dd, *J* = 5.1, 8.6 Hz, 1H), 7.12 (dd, *J* = 2.9, 8.5 Hz, 1H), 6.89 (ddd, *J* = 8.6, 8.5, 2.9 Hz, 1H), 3.05–3.00 (m, 2H), 1.34–1.29 (m, 2H), 0.29 ppm (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 160.7 (d, *J* = 246 Hz), 139.7 (d, *J* = 3 Hz), 137.9 (d, *J* = 3 Hz), 129.8 (d, *J* = 7 Hz), 120.8 (d, *J* = 19 Hz), 116.2 (d, *J* = 22 Hz), 28.9, 15.0, −1.3 ppm (2C); IR (neat): $\tilde{\nu}$ = 2952, 1452, 1243, 1201, 813, 784 cm^{-1}.

***tert*-Butyl 3,3-dimethyl-3,4-dihydrothieno[3,2-*e*][1,3]azasiline-1(2*H*)-carboxylate (20 a)**: ^1H NMR (300 MHz, $CDCl_3$): δ = 6.81 (d, *J* = 5.7 Hz, 1H), 6.59 (d, *J* = 5.7 Hz, 1H), 3.10 (s, 2H), 1.87 (s, 2H), 1.53 (s, 9H), 0.13 ppm (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 154.3, 138.3, 128.0, 119.0, 117.9, 81.5, 36.5, 28.4 (3C), 13.1, −3.2 ppm (2C); IR (neat): $\tilde{\nu}$ = 2974, 2887, 1692, 1331, 1154, 824, 698, 636 cm^{-1}.

***tert*-Butyl 1,1-dimethyl-2,3-dihydrothieno[2,3-*b*][1,4]azasiline-4(1*H*)-carboxylate 20 b.** ^1H NMR (300 MHz, $CDCl_3$): δ = 6.92 (d, *J* = 5.7 Hz, 1H), 6.84 (d, *J* = 5.7 Hz, 1H), 4.03–3.99 (m, 2H), 1.56 (s, 9H), 1.01–0.97 (m, 2H), 0.24 ppm (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ = 152.8, 151.3, 127.5, 121.1, 118.8, 82.0, 45.5, 28.3 (3C), 12.2, −1.5 ppm (2C); IR (neat): $\tilde{\nu}$ = 2974, 1695, 1365, 1287, 1149, 828, 694 cm^{-1}.

***tert*-Butyl 3,3-dimethyl-3,4-dihydropyrido[3,4-*e*][1,3]azasiline-1(2*H*)-carboxylate (21 a)**: M.p.: 134 °C; ^1H NMR (200 MHz, $CDCl_3$): δ = 8.31 (s, 1H), 8.30 (d, *J* = 8.0 Hz, 1H), 7.15 (d, *J* = 8.0 Hz, 1H), 3.01 (s, 2H), 1.92 (s, 2H), 1.46 (s, 9H), 0.13 ppm (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 154.6, 151.7, 148.3, 147.0, 129.0, 121.3, 81.2, 34.7, 28.4 (3C), 15.6, −2.7 ppm (2C); IR (neat): $\tilde{\nu}$ = 2965, 2878, 1693, 1363, 1149, 825 cm^{-1}; MS (EI, 70 eV): *m/z* (%): 278 (20) [M^+], 222 (92) [M^+−*t*Bu], 178 (92) [M^+−Boc], 163 (100) [M^+−Boc−Me]; HRMS (ESI+): *m/z* calcd for $C_{14}H_{23}N_2O_2Si$: 279.1529; found: 279.1517.

***tert*-Butyl 5-chloro-3,3-dimethyl-3,4-dihydropyrido[3,4-*e*]-[1,3]azasiline-1(2*H*)-car-boxylate (22 a)**: M.p.: 89 °C ^1H NMR (300 MHz, $CDCl_3$): δ = 8.08 (d, *J* = 5.4 Hz, 1H), 7.11 (d, *J* = 5.4 Hz, 1H), 3.02 (s, 2H), 2.15 (s, 2H), 1.46 (s, 9H), 0.17 ppm (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ = 154.2, 152.1, 150.5, 145.1, 128.5, 121.3, 81.6, 34.4, 28.3 (3C), 15.3, −2.9 ppm (2C); IR (neat): $\tilde{\nu}$ = 2962, 2874, 1707, 1578, 1373, 1314, 1144, 822 cm^{-1}; MS (CI, isobutane): *m/z* (%): 315/313 (100) [$M+H^+$], 163 (80) [$M+H^+$−*t*Bu]; HRMS (ESI+): *m/z* calcd for $C_{14}H_{22}ClN_2O_2Si$: 313.1139; found: 313.1141.

***tert*-Butyl 3,3-dimethyl-3,4-dihydropyrido[4,3-*e*][1,3]azasiline-1(2*H*)-carboxylate (23 a)**: ^1H NMR (300 MHz, $CDCl_3$): δ = 8.33 (d, *J* = 4.9 Hz, 1H), 8.30 (s, 1H), 7.13 (d, *J* = 4.9 Hz, 1H), 2.94 (A of AB quartet, *J* = 15.2 Hz, 1H), 2.73 (B of AB quartet, *J* = 15.2 Hz, 1H), 2.24 (s, 2H), 1.32 (s, 9H), 0.21 (s, 3H), 0.17 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 155.6, 148.5, 147.4, 144.3, 140.5, 125.4, 80.7, 43.9, 28.1 (3C), 17.2, −0.61 ppm (2C); IR (neat): $\tilde{\nu}$ = 2965, 1689, 1364, 1155 cm^{-1}; HRMS (ESI+): *m/z* calcd for $C_{14}H_{23}N_2O_2Si$: 279.1529; found: 279.1531.

3,3-Dimethyl-3,4-dihydro-2*H*-[1,3]oxasilino[6,5-*c*]pyridine (24 a): ^1H NMR (300 MHz, $CDCl_3$): δ = 8.22 (s, 1H), 8.09 (d, *J* = 4.5 Hz, 1H), 7.02 (d, *J* = 4.5 Hz, 1H), 3.67 (s, 2H), 2.20 (s, 2H), 0.27 ppm (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 155.8, 141.4, 136.1, 132.2, 125.3, 62.1, 15.6, −1.5 ppm (2C); HRMS (ESI+): *m/z* calcd for $C_9H_{14}NOSi$: 179.0766; found: 179.0742.

***tert*-Butyl 3,3,6-trimethyl-3,4-dihydropyrido[3,2-e][1,3]azasiline-1(2*H*)-carboxylate (25 a)**: M.p.: 98 °C; ^1H NMR (300 MHz, $CDCl_3$): δ = 8.09 (d, *J* = 1.8 Hz, 1H), 7.24 (d, *J* = 1.8 Hz, 1H), 3.09 (s, 2H), 2.27 (s, 3H), 1.89 (s, 2H), 1.44 (s, 9H), 0.11 ppm (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 155.1, 151.5, 146.0, 139.3, 131.2, 128.7, 80.2, 34.9, 28.5 (3C), 18.7, 18.0, −2.6 ppm (2C); IR (neat): $\tilde{\nu}$ = 2959, 1693, 1361, 1158, 837 cm^{-1}; HRMS (ESI+): *m/z* calcd for $C_{15}H_{25}N_2O_2Si$: 293.1685; found: 293.1675.

7-Chloro-3,3-dimethyl-1,2,3,4-tetrahydropyrido[3,2-*e*]-[1,3]azasiline (26 a): M.p.: 128 °C ^1H NMR (300 MHz, $CDCl_3$): δ = 7.09 (d, *J* = 7.3 Hz, 1H), 6.50 (d, *J* = 7.3 Hz, 1H), 4.84 (brs, 1H), 2.72 (d, *J* = 3.0 Hz, 2H), 1.90 (s, 2H), 0.14 ppm (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 158.3, 146.1, 142.5, 114.6, 112.5, 31.7, 16.5, −3.6 ppm (2C); IR (neat): $\tilde{\nu}$ = 3284, 2957, 2895, 1589, 1247 cm^{-1}.

3-Methyl-3-phenyl-3,4-dihydro-2*H*-benzo-1,3-oxasiline (37 a): ^1H NMR (300 MHz, $CDCl_3$): δ = 7.51–7.48 (m, 2H), 7.41–7.33 (m, 3H), 7.14–7.10 (m, 2H), 6.98–6.94 (m, 2H), 4.03 (d, *J* = 14.7 Hz, 1H), 3.94 (d, *J* = 14.7 Hz, 1H), 2.33 (d, *J* = 15.6 Hz, 1H), 2.19 (d, *J* = 15.6 Hz, 1H), 0.47 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 158.4, 135.6, 134.0 (2C), 132.1, 130.0, 128.2 (2C), 127.7, 126.9, 123.0, 119.8, 63.6, 15.6, −5.0 ppm ; MS (CI, isobutane): *m/z* (%): 241 (58) [$M+H^+$], 163 (100) [M−Ph].

4-Methyl-4-phenyl-3,4-dihydro-2 *H*-benzo-1,4-oxasiline (37 b): ^1H NMR (300 MHz, $CDCl_3$): δ = 7.56–7.53 (m, 2H), 7.40–7.27 (m, 5H), 6.98–6.89 (m, 2H), 4.45–4.30 (m, 2H), 1.38–1.31 (m, 2H), 0.59 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 165.3, 136.9, 135.6, 134.5 (2C), 131.3, 129.7, 128.1 (2C), 121.2, 119.0, 117.8, 66.7, 13.7, −3.0 ppm; IR (neat): $\tilde{\nu}$ = 3056, 2956, 2861, 1429, 1210, 759, 696, 422 cm^{-1}.

3-Methyl-3-phenyl-3,4-dihydro-2*H*-benzo-1,3-oxasiline (38 a): ^1H NMR (300 MHz, $CDCl_3$): δ = 7.53–7.50 (m, 4H), 7.43–7.33 (m, 6H), 7.18–7.09 (m, 2H), 6.99–6.95 (m, 2H), 4.27 (s, 2H), 2.55 ppm (s, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 158.4, 134.8 (4C), 133.4, 132.0, 130.0 (2C), 128.1 (4C), 127.1, 126.9, 123.0, 119.7 (2C), 62.7, 14.4 ppm.

4-Methyl-4-phenyl-3,4-dihydro-2*H*-benzo-1,4-oxasiline (38 b): ^1H NMR (300 MHz, $CDCl_3$): δ = 7.61–7.58 (m, 4H), 7.43–7.33 (m, 8H), 6.99–6.92 (m, 2H), 4.45–4.41 (m, 2H), 1.65–1.61 ppm (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 165.5, 136.5, 135.4 (4C), 134.4, 131.5, 129.8 (2C), 128.0 (4C), 121.1, 117.9 (2C), 116.9, 66.5, 15.5 ppm.

3-Benzyl-3-methyl-2,3-dihydrobenzo[*d*][1,3]oxasilole (38 c): ^1H NMR (300 MHz, $CDCl_3$): δ = 7.53–7.50 (m, 2H), 7.40–7.33 (m, 5H), 7.19–7.08 (m, 3H), 6.99–6.84 (m, 4H), 4.04 (s, 2H), 2.82 (A of AB quartet, *J* = 15.0 Hz, 1H), 2.72 ppm (B of AB quartet, *J* = 15.0 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 169.3, 137.1, 134.7 (2C), 133.7, 133.2, 132.3, 130.2, 128.6 (2C), 128.4 (2C), 128.1 (2C), 124.9, 120.5, 117.0, 112.9, 60.4, 22.3 ppm; HRMS (ESI+): *m/z* calcd for $C_{20}H_{18}OSi$: 302.1127; found: 302.1120.

***tert*-Butyl 4-methyl-4-phenyl-3,4-dihydrobenzo[*b*][1,4]azasiline-1(2*H*)-carboxylate (40 b)**: ^1H NMR (300 MHz, $CDCl_3$): δ = 7.53–7.47 (m, 2H), 7.41–7.28 (m, 6H), 7.13 (ddd, *J* = 7.3, 7.2, 1.5 Hz, 1H), 4.12–3.99 (m, 1H), 3.87–3.76 (m, 1H), 1.55–1.43 (m, 1H), 1.47 (s, 9H), 1.37–1.25 (m, 1H), 0.59 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 154.0, 149.3, 137.1, 134.3, 134.1 (2C), 129.4, 129.3, 128.6, 127.9 (2C), 126.2, 124.8, 80.3, 45.1, 28.3 (3C), 13.9, −3.2 ppm; HRMS (ESI+): *m/z* calcd for $C_{20}H_{26}NO_2Si$: 340.1733; found: 340.1736.

***tert*-Butyl 4,4-diphenyl-3,4-dihydrobenzo[*b*][1,4]azasiline-1(2*H*)-carboxylate (41 b)**: ^1H NMR (300 MHz, $CDCl_3$): δ = 7.54–7.51 (m, 4H), 7.41–7.36 (m, 9H), 7.13 (dd, *J* = 7.0, 1.6 Hz, 1H), 4.03–3.99 (m, 2H), 1.71–1.67 (m, 2H), 1.37 ppm (s, 9H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 154.0, 149.8, 135.4, 135.3 (4C), 134.7 (2C), 129.7 (2C), 129.6,

128.0 (4C), 127.0, 126.4, 124.9, 80.3, 45.1, 28.2 (3C), 13.2 ppm; HRMS (ESI+): *m/z* calcd for $C_{25}H_{28}NO_2Si$: 402.1889; found: 402.1894.

***tert*-Butyl 3-benzyl-3-phenyl-2,3-dihydro-1*H*-benzo[*d*]-[1,3]azasilole-1-carboxylate (41 c)** : ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=$ 8.24 (d, $J=8.6$ Hz, 1H), 7.56–7.45 (m, 2H), 7.43–7.30 (m, 5H), 7.18–7.03 (m, 3H), 7.02–6.89 (m, 3H), 3.29 (s, 2H), 2.79 (A of AB quartet, $J=14.1$ Hz, 1H), 2.68 (B of AB quartet, $J=14.1$ Hz, 1H), 1.54 ppm (s, 9H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=154.3$, 152.6, 137.1, 135.3, 134.7 (2C), 133.6, 131.5, 130.2, 128.6 (2C), 128.4 (2C), 128.1 (2C), 127.9, 124.9, 122.0, 118.1, 80.7, 35.6, 28.4 (3C), 22.6 ppm; MS (CI, isobutane): *m/z* (%): 402 (11) [$M+H^+$], 346 (100) [$M+H^+-t$Bu], 302 (55) [$M+H^+-$Boc].

***tert*-Butyl 3-methyl-3-phenyl-3,4-dihydropyrido[3,4-*e*]-[1,3]azasiline-1(2*H*)-carboxylate (42 a)**: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=$8.35–8.33 (m, 2H), 7.44–7.31 (m, 5H), 7.22 (d, $J=5.7$ Hz, 1H), 3.38 (d, $J=15.0$ Hz, 1H), 3.20 (d, $J=15.0$ Hz, 1H), 2.22 (d, $J=$ 15.0 Hz, 1H), 2.11 (d, $J=15.0$ Hz, 1H), 1.48 (s, 9H), 0.42 ppm (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=154.3$, 151.7, 148.4, 147.0, 134.6, 133.6 (2C), 130.1, 128.5, 128.1 (2C), 121.2, 81.2, 34.2, 28.2 (3C), 14.8, −4.5 ppm.

***tert*-Butyl 3,3-diphenyl-3,4-dihydropyrido[3,4-*e*][1,3]azasiline-1(2*H*)-carboxylate (43 a)**: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=8.06$ (d, $J=$ 5.4 Hz, 2H), 7.52–7.36 (m, 11H), 3.62 (s, 2H), 2.47 (s, 2H), 1.48 ppm (s, 9H).

***tert*-Butyl 3-benzyl-3-phenyl-2,3-dihydro-1*H*-[1,3]azasilolo[4,5-*c*]pyridine-1-carboxylate (43 c)**: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=$ 8.42–8.40 (m, 2H), 7.47–7.28 (m, 4H), 7.19–7.01 (m, 5H), 6.86–6.85 (m, 2H), 3.25 (A of AB quartet, $J=15.3$ Hz, 1H), 3.15 (B of AB quartet, $J=15.3$ Hz, 1H), 2.50 (A of AB quartet, $J=13.8$ Hz, 1H), 2.43 (B of AB quartet, $J=13.8$ Hz, 1H), 1.33 ppm (s, 9H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=154.7$, 151.4, 150.1, 147.0, 137.7, 135.1, 133.8 (2C), 129.8 (2C), 128.6 (2C), 128.4(2C), 127.7, 124.7, 119.74, 119.68, 82.3, 41.1, 28.0 (3C), 25.0 ppm.

3,3-Dimethyl-3,4-dihydro-2 H-benzo[e][1,3]oxagermine (54 a): ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=$7.30–7.27 (m, 1H); 7.11–7.06 (m, 2H), 6.99–6.94 (m, 1H), 3.92 (s, 2H), 2.12 (s, 2H), 0.31 ppm (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=158.0$, 131.2, 130.9, 126.6, 123.5, 120.5, 66.0, 16.5, −3.3 (2C); MS (CI, isobutane) *m/z* (%): 265 (8) [$M+C_3H_7^+$], 224 (100) [$M+H^+$], 209 (30) [$M-$Me].

4,4-Dimethyl-3,4-dihydro-2*H*-benzo[b][1,4]oxagermine (54 b): ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=7.75$ (dd, $J=8.2$, 1.5 Hz, 1H), 7.32–7.30 (m, 1H), 6.94–6.86 (m, 1H), 6.72–6.69 (m,1H), 4.32–4.27 (m, 2H), 1.40–1.36 (m, 2H), 0.43 ppm (6H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=164.6$, 136.4, 130.1, 127.0, 121.8, 118.1, 68.2, 15.8, −1.8 ppm (2C).

3,3-Dimethyl-2,3-dihydrobenzo[d][1,3]oxagermole (54 d): ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=7.48$ (dd, $J=6.9$, 1.5 Hz, 1H), 7.29–7.24 (m, 1H), 6.94–6.86 (m, 2H), 4.08 (s, 2H), 0.59 ppm (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=165.8$, 134.8, 132.8, 131.0, 120.5, 113.0, 62.8, −1.5 ppm (2C); MS (CI, isobutane): *m/z* (%): 211 (100) [$M+H^+$].

4,4-Dimethyl-3,4-dihydro-2 *H*-benzo[*b*][1,4]thiagermine (55 b): ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=$7.40–7.37 (m, 1H), 7.30–7.27 (m, 1H), 7.18–7.15 (m, 2H), 3.05–3.01 (m, 2H), 1.56–1.52 (m, 2H), 0.42 ppm (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=145.0$, 139.0, 134.5, 129.1, 128.5, 125.7, 31.0, 18.3, −1.5 ppm (2C); IR (neat) : $\tilde{\nu}=3050$, 2966, 2903, 1421, 1150, 744 cm^{-1}; MS (CI, isobutane): *m/z* (%): 240 (22) [$M+H^+$], 213 (100), 209 (55) [$M-$2Me].

***tert*-Butyl 4,4-dimethyl-3,4-dihydrobenzo[*b*][1,4]azagermine-1(2*H*)-carboxylate (56 b)**: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=$7.37–7.33 (m, 1H), 7.30–7.25 (m, 2H), 7.17–7.12 (m, 1H), 3.79–3.75 (m, 2H), 1.50–1.44 (m, 9H), 1.44–1.40 (m, 2H), 0.37 ppm (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=154.3$, 148.7, 133.5, 129.1, 128.5, 126.4, 125.4, 80.2, 46.0, 28.5 (3C), 16.1, −1.7 ppm (2C); IR (neat) : $\tilde{\nu}=2971$, 2929, 2901,1694, 1421, 802, 744 cm^{-1}; MS (CI, isobutane) *m/z* (%): 323 (11) [$M+H^+$], 306 (11) [$M+H^+-$Me], 268 (100) [$M+H^+-t$Bu], 222 (22) [$M-$Boc]; HRMS (ESI+): *m/z* calcd for $C_{17}H_{26}N_2O_2GeNa$: 387.1114 [$M+$Na+MeCN]; found: 387.1104.

***tert*-Butyl 3,3-dimethyl-2,3-dihydro-1*H*-benzo[*d*][1,3]azagermole-1-carboxylate (56 d)**: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=8.24$ (d, $J=$ 8.4 Hz, 1H), 7.45 (dd, $J=7.5$, 1.5 Hz, 1H), 7.31 (ddd, $J=8.4$, 7.5, 1.5 Hz, 1H), 6.99 ($t_{ap.}$, $J=7.5$ Hz, 1H), 3.27 (s, 2H), 1.57 (s, 9H), 0.53 ppm (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=155.0$, 149.3, 132.5, 130.1, 129.6, 122.2, 118.6, 80.7, 37.8, 28.6 (3C), −1.7 ppm (2C); MS (CI, isobutane) *m/z* (%): 309 (11) [$M+H^+$], 292 (9) [$M-$Me], 254 (100) [$M+H^+-t$Bu], 210 (37) [$M+H^+-$Boc].

***tert*-Butyl 6-(dibenzylamino)-3,3-dimethyl-2,3-dihydro-1*H*-benzo[*d*][1,3]azagermole-1-carboxylate (57 b)**: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=$7.37–7.20 (m, 10H), 7.15 (d, $J=8.2$ Hz, 1H), 6.70 (brs, 1H), 6.60 (dd, $J=8.2$, 2.5 Hz, 1H), 4.63 (s, 4H), 3.80–3.72 (m, 2H), 1.37 (s, 9H), 1.39–1.29 (m, 2H), 0.34 ppm (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=154.2$, 149.8, 149.6, 138.5 (2C), 133.9, 128.6 (4C), 126.9 (2C), 126.6 (4C), 119.7, 110.4, 110.2, 79.7, 53.8 (2C), 46.1, 28.3 (3C), 15.8, −1.6 ppm (2C); IR (neat) : $\tilde{\nu}=3296$, 2928, 1689, 1595, 1363, 1150, 1014, 730, 695 cm^{-1}; HRMS (ESI+): *m/z* calcd for $C_{29}H_{37}N_2O_2{}^{72}Ge$: 517.2076; found: 517.2094.

***tert*-Butyl 7-(dibenzylamino)-4,4-dimethyl-3,4-dihydrobenzo[*b*]-[1,4]azagermine-1(2*H*)-carboxylate (57 d)**: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=7.82$ (brs, 1H), 7.38–7.19 (m, 11H), 6.41 (dd, $J=8.1$, 2.2 Hz, 1H), 4.66 (s, 4H), 3.26 (s, 2H), 1.45 (s, 9H), 0.48 ppm (s, 6H); ^{13}C NMR (50 MHz, $CDCl_3$): $\delta=154.8$, 151.1, 150.8, 138.5 (2C), 132.9, 128.5 (4C), 126.9 (2C), 126.8 (4C), 116.2, 107.2, 102.7, 80.4, 53.7 (2C), 38.7, 28.3 (3C), −1.7 ppm (2C); IR (neat) : $\tilde{\nu}=3308$, 2973, 1694, 1592, 1326, 1154, 727, 694 cm^{-1}; HRMS (ESI+): *m/z* calcd for $C_{28}H_{35}N_2O_2{}^{72}Ge$: 503.1919; found: 503.1930.

3,3-Dimethyl-1-tosyl-1,2,3,4-tetrahydrobenzo[e][1,3]azagermine (58 a): ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=7.41$ (d, $J=8.2$ Hz, 2H), 7.30 (d, $J=7.3$ Hz, 2H), 7.18 (d, $J=8.0$ Hz, 2H), 7.07–7.02 (m, 2H), 3.33 (s, 2H), 2.60 (s, 2H), 2.43 (s, 3H), 0.15 ppm (s, 6H); HRMS (ESI+): *m/z* calcd for $C_{17}H_{21}NO_2GeSNa$: 400.0402; found: 400.0409.

4,4-Dimethyl-1-tosyl-1,2,3,4-tetrahydrobenzo[b][1,4]azagermine (58 b): ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=$7.60–7.57 (m, 1H), 7.46 (d, $J=$ 8.0 Hz, 2H), 7.30 (d, $J=7.3$ Hz, 2H), 7.27–7.21 (m, 1H), 7.18 (d, $J=$ 8.0 Hz, 2H), 4.03–3.99 (m, 2H), 2.36 (s, 3H), 1.27–1.23 (m, 2H), 0.05 ppm (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=146.3$, 143.3, 138.6, 135.0, 134.2, 129.6 (2C), 129.2, 127.5 (2C), 127.3, 126.6, 48.9, 21.6, 14.5, −1.9 ppm (2C); HRMS (ESI+): calcd for $C_{19}H_{24}N_2O_2GeSNa$: 441.0668 [$M+$MeCN$+H^+$]; found: 441.0679.

***tert*-Butyl 3,3-dimethyl-7-(trifluoromethyl)-3,4-dihydrobenzo[*e*]-[1,3]azagermine-1(2*H*)-carboxylate (59 a)**: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=7.39$ (brs, 1H), 7.33 (d, $J=7.8$ Hz, 1H), 7.21 (d, $J=7.8$ Hz, 1H), 3.10 (brs, 2H), 2.09 (s, 2H), 1.41 (s, 9H), 0.29 ppm (6H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=154.7$, 140.8, 140.4, 129.9, 127.7 (q, $J=33$ Hz), 125.2 (q, $J=4$ Hz), 124.3 (q, $J=270$ Hz), 122.7 (q, $J=$ 4 Hz), 80.5, 35.3, 28.4 (3C), 19.2, −2.9 ppm (2C); ^{19}F NMR ($CFCl_3$): $\delta=-62.25$ ppm (s, 3F); IR (neat) : $\tilde{\nu}=2983$, 2897, 1690, 1334, 1122, 834, 610 cm^{-1}.

***tert*-Butyl 3,3-dimethyl-3,4-dihydropyrido[3,4-*e*][1,3]azagermine-1(2*H*)-carboxylate (60 a)**: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=8.35$ (s, 1H), 8.31 (d, $J=5.4$ Hz, 1H), 7.08 (d, $J=5.4$ Hz, 1H), 3.15 (s, 2H), 2.02 (s, 2H), 1.44 (s, 9H), 0.30 ppm (6H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=154.2$, 151.1, 147.9, 146.9, 130.8, 122.0, 80.9, 34.9, 28.2 (3C), 15.0, −3.0 ppm (2C); IR (neat): $\tilde{\nu}=2979$, 2902, 1690, 1367, 1156, 819, 611 cm^{-1}.

***tert*-Butyl 3,3-dimethyl-3,4-dihydropyrido[4,3-*e*][1,3]azagermine-1(2*H*)-carboxylate (61 a)**: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 8.27$ (s, 1H), 8.17 (d, $J = 4.8$ Hz, 1H), 6.99 (d, $J = 4.8$, 1H), 3.15 (brs, 2H), 1.99 (s, 2H), 1.36 (s, 9H), 0.26 ppm (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta =$ 154.5, 148.7, 146.5, 144.9, 137.4, 124.1, 80.6, 30.3, 28.3 (3C), 18.7, −2.9 ppm (2C); IR (neat) : $\tilde{\nu} = 2976$, 2908, 1365, 1154, 833 cm^{-1}; HRMS (ESI+): *m/z* calcd for $C_{14}H_{23}GeN_2O_2$: 325.0971; found: 325.0974.

3,3-Dimethyl-3,4-dihydro-2*H*-[1,3]oxagermino[5,6-*c*]pyridine (62 a): ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 8.18$ (s, 1H), 8.13 (d, $J = 5.0$ Hz, 1H), 7.04 (d, $J = 5.0$, 1H), 3.95 (s, 2H), 2.09 (s, 2H), 0.32 ppm (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 153.7$, 144.7, 142.3, 140.3, 125.4, 60.1, 16.2, −3.2 ppm (2C).

***tert*-Butyl 4-methyl-3,3-dimethyl-2,3-dihydro-1*H*-benzo[*d*]-[1,3]azagermole-1-carboxylate (63 d)**: ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 8.09$ (d, $J = 8.4$ Hz, 1H), 7.23–7.21 (m, 1H), 6.82 (d, $J = 7.2$ Hz, 1H), 3.26 (s, 2H), 2.38 (s, 3H), 1.58 (s, 9H), 0.58 ppm (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 155.0$, 149.3, 142.1, 130.6, 129.1, 122.6, 116.0, 80.6, 37.6, 28.6 (3C), 23.1, −1.9 ppm (2C); IR (neat) : $\tilde{\nu} = 2971$, 2903, 1699, 1319, 1125, 778 cm^{-1}; MS: *m/z* (%): 320/322/324 (30) [$M+H^+$], 305/307/309 (100) [$M-$Me], 264/266/268 (75) [M<*M*->*t*Bu]; HRMS (ESI+): *m/z* calcd for $C_{15}H_{24}NO_2Ge$: 324.1019; found: 324.1021.

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