

Selenostannylation of Arynes Produced by Silylaryl Triflates under Mild Reaction Conditions

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Tributil[(fenilselanyl)aryl]estannanes foram preparadas em bons rendimentos por reação entre tributil(fenilselanyl)estannana e 2-(trimetilsilil)aryl triflato na presença de fluoreto de potássio e éter 18-coroa-6 em THF a 0 °C.

Tributyl[(phenylselanyl)aryl]stannanes were prepared in good yields by reaction between tributyl(phenylselanyl)stannane and 2-(trimethylsilyl)aryl triflates in the presence of potassium fluoride and 18-crown-6 ether in THF at 0 °C.

Keywords: benzyne, arynes, insertion reaction, selenostannanes

Introduction

Benzyne is an important reactive intermediate in synthetic organic chemistry which has found application in several total syntheses¹ and in the preparation of functional materials.² Accordingly, a number of methods for benzyne formation have been reported in the literature.³⁻⁸ Among them we pay particular attention to the thermal decompositions of benzenediazonium-2-carboxylate⁴ and diphenyliodonium-2-carboxylate,⁵ the elimination reaction resulted from oxidative addition of magnesium in 2-bromofluorobenzene,⁶ the iodine-magnesium exchange reaction followed by elimination occurred in 2-iodophenyl 4-chlorobenzenesulfonate,⁷ and the oxidation of 1-aminobenzotriazole in the presence of lead tetraacetate.⁸

Although the methodologies for generating benzyne which were mentioned above are of great importance in the context of benzyne chemistry,³⁻⁸ they have employed harsh conditions, including high temperatures, strong bases or powerful oxidizing agents.³⁻⁸ In this scenario, 2-(trimethylsilyl)aryl triflates⁹ and phenyl[2-(trimethylsilyl)aryl]iodonium triflates¹⁰ arise as promising reagents to form arynes under mild reaction conditions.^{9,10} Once

2-(trimethylsilyl)phenyl triflate was transformed in a commercially available reagent and its derivatives can be easily prepared from phenols,⁹ 2-(trimethylsilyl)aryl triflates have emerged as remarkable reagents for generating arynes recently employed in several insertion reactions into sigma bonds.¹¹ Because of the highly electrophilic character of arynes that comes from their low-energy LUMOs, even neutral nucleophiles of diminished nucleophilicity readily attacks arynes to produce zwitterions, which act as key intermediates in the insertion reactions into, for example, C-C,¹² N-H,^{13,14} O-H,^{14,15} Se-Se,^{16,17} Te-Te¹⁷ and S-Sn¹⁸ sigma bonds. These transformations lead to the formation of polysubstituted arenes and benzoannulated compounds, which would be hardly synthesized in just one step by other methods.

In this work, we report our results involving the insertion reaction of arynes generated from 2-(trimethylsilyl)aryl triflates under mild reaction conditions into Se-Sn sigma bond of tributyl(phenylselanyl)stannane,¹⁹ as an attractive alternative for the synthesis of tributyl[(phenylselanyl)aryl]stannanes²⁰ in good yields.

The organometallic compounds produced by the selenostannylation process can be considered versatile intermediates in synthetic organic chemistry, finding application in cross-coupling reactions, transmetallations and iodolyses.¹⁸ In order to give some support to this fact,

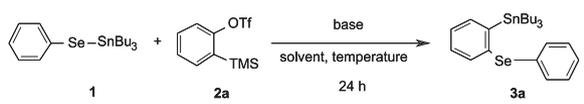
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we subjected one of the aromatic selenostannanes produced in the course of our investigation to the iododestannylation reaction and the result obtained was enclosed herein.

Results and Discussion

Allowing the reaction of tributyl(phenylselanyl)stannane (**1**) with 1.5 equiv. of 2-(trimethylsilyl)phenyl triflate (**2a**) and 3 equiv. of CsF in acetonitrile at room temperature, we obtained tributyl[2-(phenylselanyl)phenyl]stannane (**3a**) in a very low yield (< 5%) (Table 1, entry 1). In an attempt to improve the obtained yield (entry 1), subsequent work focused on optimization of these reaction conditions (Table 1).

Table 1. Optimization of the synthesis of tributyl[2-(phenylselanyl)phenyl]stannane (**3a**) (equation 1)^a



Entry	2a (equiv.)	base (equiv.)	solvent	T (°C)	isolated yield (%)
1	1.5	CsF (3)	MeCN	rt	< 5
2	1.5	KF/18-crown-6 ether (1.5/1.5)	THF	0	52
3	1.5	<i>n</i> -Bu ₄ NF (1.8)	THF	rt	0 ^b
4	2	KF/18-crown-6 ether (2/2)	THF	0	62
5	2	KF/18-crown-6 ether (2/2)	THF	rt	57
6	2.5	KF/18-crown-6 ether (2.5/2.5)	THF	0	60
7	2	18-crown-6 ether (2)	THF	0	0

^aReaction conditions: 0.3 mmol of the stannyl selenide **1**, the indicated amount of the benzyne precursor **2a**, the indicated amount of base, and 3 mL of solvent were stirred at the temperature indicated for 24 h. ^bThis reaction was stirred for 3 h.

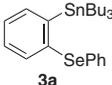
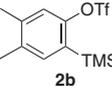
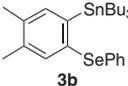
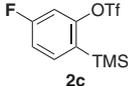
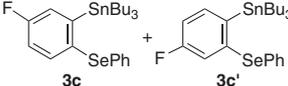
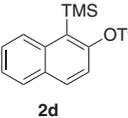
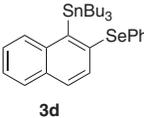
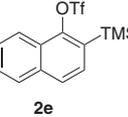
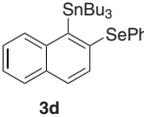
In order to examine the effect of the fluoride ion sources on the transformation, we carried out the reaction of tributyl(phenylselanyl)stannane (**1**) with 1.5 equiv. of 2-(trimethylsilyl)phenyl triflate (**2a**), 1.5 equiv. of KF and 1.5 equiv. of 18-crown-6 ether in THF at 0 °C for 24 h and obtained tributyl[2-(phenylselanyl)phenyl]stannane (**3a**) in a moderate yield of 52% (Table 1, entry 2). By performing the reaction of the stannyl selenide **1** with 1.5 equiv. of the benzyne precursor **2a** in the presence of 1.8 equiv. of tetrabutylammonium fluoride (TBAF) in THF at room temperature for 3 h, the insertion product **3a** was not produced (entry 3). No further attempts were made to optimize this TBAF procedure. Afterwards, we

treated tributyl(phenylselanyl)stannane (**1**) with 2 equiv. of 2-(trimethylsilyl)phenyl triflate (**2a**), 2 equiv. of KF and 2 equiv. of 18-crown-6 ether in THF at 0 °C for 24 h to give tributyl[2-(phenylselanyl)phenyl]stannane (**3a**) in a good 62% yield (entry 4). When the same reaction was carried out at room temperature, compound **3a** was obtained in a slightly lower yield of 57% (entry 5). No significant improvement in the isolated yield of tributyl[2-(phenylselanyl)phenyl]stannane (**3a**) was obtained when we allowed the stannyl selenide **1** to react with 2.5 equiv. of the benzyne precursor **2a** in the presence of 2.5 equiv. of KF and 2.5 equiv. of 18-crown-6 ether at 0 °C for 24 h (entry 6). As can be seen in Table 1, entry 7, compound **3a** was not obtained and the starting materials **1** and **2a** were recovered when the reaction was carried out in the absence of KF. This experiment shows that the success of our reaction depends dramatically on the presence of a fluoride ions source.

Employing the optimal conditions shown in Table 1, entry 4,²¹ we examine the scope and limitations of the process (Table 2). The reaction between tributyl(phenylselanyl)stannane (**1**) and the electron-rich aryne precursor **2b** gave the aromatic selenostannane **3b** in a 60% isolated yield (entry 2). To better understand the regioselectivity of the reaction when unsymmetrical arynes are employed, we treated tributyl(phenylselanyl)stannane (**1**) with the 4-fluoro aryne precursor **2c** and obtained a mixture of isomers **3c** and **3c'** in a 2:1 ratio with a total yield of 34% (entry 3). In this case, the electron-withdrawing group promoted a more sluggish transformation leading to a regioisomeric mixture of products in a moderate yield. In addition, the major product **3c** was obtained by the attack of the stannyl selenide **1** at the electronically most favorable position of the fluorinated aryne formed from compound **2c**. This result indicates that our reaction involves the formation of benzyne and its derivatives as intermediates. Trying to give support to the formation of arynes as intermediates in this selenostannylation process, we allowed the reaction of tributyl(phenylselanyl)stannane (**1**) with the silylaryl triflates **2d** and **2e**, and the same aromatic selenostannane **3d** was produced in 55 and 54% yields, respectively (Table 2, entries 4 and 5). The formation of the same insertion product **3d** from the silylaryl triflates **2d** (entry 4) and **2e** (entry 5) suggests the generation of 1,2-naphthalene as a common intermediate for the transformations. Besides, we have to mention that the exclusive formation of the regioisomer **3d** in both reactions (Table 2, entries 4 and 5) can be rationalized by steric factors related to the attack of the stannyl selenide **1** to the 1,2-naphthalene intermediate.²²

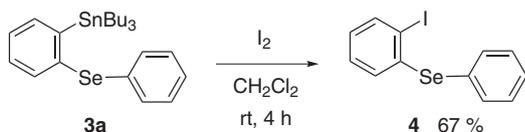
The products from the selenostannylation of arynes (**3a-d**) are versatile reagents in organic synthesis, which can find

Table 2. Synthesis of tributyl[(phenylselenanyl)aryl]stannanes (**3**) by the reaction of tributyl(phenylselenanyl)stannane (**1**) with 2-(trimethylsilyl)aryl triflates (**2**) in the presence of KF and 18-crown-6 ether using THF as solvent^a

Entry	stannyl selenide (1)	aryne precursor (2)	insertion product (3)	isolated yield (%)
1				62
2	1			60
3	1			34 (2:1) ^b
4	1			55
5	1			54

^aReaction conditions: 0.3 mmol of tributyl(phenylselenanyl)stannane (**1**), 0.6 mmol of 2-(trimethylsilyl)aryl triflate (**2**), 0.6 mmol of potassium fluoride, 0.6 mmol of 18-crown-6 ether, and 3 mL of THF were stirred at 0 °C for 24 h. ^bThe ratio was determined by ¹H NMR spectroscopy.

application in cross-coupling reactions, homocouplings and in iodolyses. Accordingly, we subjected the stannane **3a** to the reaction with iodine and obtained the diphenylselenide iodinated **4** in a good isolated yield of 67% (Scheme 1).

**Scheme 1.** Iodolysis of tributyl[2-(phenylselenanyl)phenyl]stannane (**3a**).

The structures of compounds **3a-d** and **4** were assigned on the basis of a variety of spectroscopic techniques, namely, according to their IR, ¹H, and ¹³C NMR spectra. The compounds **3a-d** provided elemental analyses that agree with the proposed structures. Compound **4** presented LRMS that agrees with its structure and the mixture of regioisomers **3c** and **3c'**, and compound **3d** had their ⁷⁷Se NMR spectra recorded.

Conclusions

In summary, a simple procedure which involves mild reaction conditions for the selenostannylation of arynes was developed and aromatic selenostannanes were produced in good yields. This attractive process provides an alternative

for the preparation of organometallic compounds which are hardly synthesized in just one step by other methods and should find applications in the construction of molecules with interesting biological properties and in the preparation of functional materials.

Acknowledgments

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Supplementary Information

Experimental data and NMR spectra are available free of charge at <http://jbcs.sbq.org.br>, as PDF file.

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21. *General procedure for selenostannylation of arynes*: To a vial (10 mL) were added the tributyl(phenylselanyl)stannane **1** (0.3 mmol), the appropriate aryne precursor **2a-e** (0.6 mmol), 18-crown-6 ether (158 mg, 0.6 mmol), and THF (3 mL). The mixture was cooled to 0 °C and potassium fluoride (34.8 mg, 0.6 mmol) was added. The vial was sealed using a cap, and the reaction mixture was stirred for 24 h at 0 °C. Afterwards, the reaction was added to a saturated solution of ammonium chloride (30 mL), which was extracted with ethyl acetate (3 × 30 mL). The organic phase was dried over MgSO₄. After filtration, the solvent was evaporated under reduced pressure. The residue was purified by preparative TLC using silica gel as stationary phase and hexane as eluent unless otherwise indicated, affording the desired products **3a-d**. Tributyl[2-(phenylselanyl)phenyl]stannane (**3a**): yield 97.1 mg (62%); light yellow oil; ¹H NMR (CDCl₃, 300 MHz) δ: 7.52 (dd, *J* 7.5 Hz, *J* 1.3 Hz, 1H), 7.45 (dd, *J* 7.5 Hz, *J* 1.6 Hz, 1H), 7.30-7.13 (m, 7H), 1.55-1.44 (m, 6H), 1.27 (sext, *J* 7.3 Hz, 6H), 1.08-1.03 (m, 6H), 0.84 (t, *J* 7.3 Hz, 9H); ¹³C NMR (CDCl₃, 75 MHz) δ: 151.4, 139.2, 137.5, 135.8, 134.0, 130.5, 129.3, 129.1, 127.3, 126.3, 29.1, 27.4, 13.7, 11.2; IR (film) ν_{max}/cm⁻¹: 2956,

2923, 1926, 1849, 1793, 1732, 1578, 1470, 1441, 1070, 736, 689; Elemental Analysis: calc. for $C_{24}H_{36}SeSn$: C 55.20; H 6.95%; found: C 55.20; H 6.85%.

22. The structure proposed for regioisomer **3d** is according to the pattern of regioselectivity followed by a number of insertion reactions of 1,2-naphthalene into nucleophile-electrophile sigma bonds, see: Yoshida, H.; Shirakawa, E.; Honda, Y.; Hiyama, T.; *Angew. Chem., Int. Ed.* **2002**, *41*, 3247; Yoshida, H.; Fukushima, H.; Morishita, T.; Ohshita, J.; Kunai, A.;

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General methods

¹H and ¹³C NMR spectra were obtained on a Varian INOVA 300 spectrometer (¹H at 300 MHz and ¹³C at 75 MHz) and on a Bruker DRX-500 spectrometer (¹H at 500 MHz and ¹³C at 125 MHz). The spectra were taken in deuterated solvents and the chemical shifts were given in ppm using residual undeuterated solvents or tetramethylsilane (TMS) as internal standard. ⁷⁷Se NMR spectra were taken on a Bruker DRX-500 spectrometer at 95 MHz using CDCl₃ as solvent. The chemical shifts were given in ppm using diphenyl diselenide (PhSeSePh) diluted in CDCl₃ (1 mol L⁻¹) as an external standard (δ 463 ppm at 25°C). Low-resolution mass spectra were obtained on a Shimadzu CG-17A/CGMS-QP5050A instrument. Elemental analyses were obtained on a Perkin-Elmer CHN 2400 equipment. Near-IR spectra were obtained on a Bomem MB-100 spectrometer. The melting point value obtained is uncorrected. Reagents and solvents were used as obtained commercially or when necessary were purified and/or dried using procedures described in the literature.¹ THF was distilled under nitrogen from sodium/benzophenone and CH₃CN was distilled from calcium hydride. Both solvents were distilled prior to use. Oxygen and moisture sensitive materials were manipulated under a nitrogen atmosphere. Column chromatography and preparative thin layer chromatography separations were carried out using silica gel 60. Tributyl(phenylselanyl)stannane (**1**),² 2-(trimethylsilyl)phenyl triflate (**2a**),³ 4,5-dimethyl-2-(trimethylsilyl)phenyl triflate (**2b**),⁴ 4-fluoro-2-(trimethylsilyl)phenyl triflate (**2c**),⁵ 1-(trimethylsilyl)-2-naphthyl triflate (**2d**),⁶ and 2-(trimethylsilyl)-1-naphthyl triflate (**2e**)⁷ were prepared according to literature procedures.

General procedure for selenostannylation of arynes

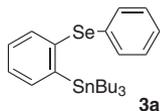
To a vial (10 mL) were added the tributyl(phenylselanyl)stannane **1** (0.3 mmol), the appropriate aryne precursor **2a-e** (0.6 mmol), 18-crown-6 ether (158 mg, 0.6 mmol), and THF (3 mL). The mixture was cooled to 0 °C and potassium fluoride (34.8 mg, 0.6 mmol) was added. The vial was sealed using a cap, and the reaction mixture was stirred for 24 h at 0 °C. Afterwards, the reaction was added to a saturated solution of ammonium chloride (30 mL), which was extracted with ethyl acetate (3 × 30 mL). The organic phase was dried over MgSO₄. After filtration, the solvent was evaporated under reduced pressure. The residue was purified by preparative TLC using silica gel as stationary phase and hexane as eluent unless otherwise indicated, affording the desired products **3a-d**.

Iododestannylation of aromatic selenostannane

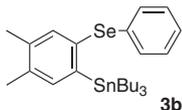
To a vial (10 mL) were added the tributyl[2-(phenylselanyl)phenyl]stannane **3a** (47.5 mg, 0.09 mmol), dichloromethane (1 mL), and iodine (23 mg, 0.09 mmol). The vial was sealed using a cap, and the mixture was stirred for 4 h at room temperature. Afterwards, the reaction was diluted with ethyl acetate (10 mL) and washed with a saturated solution of sodium thiosulfate (10 mL). The organic phase was stirred with an 1 mol.L⁻¹ aqueous solution of potassium fluoride (10 mL) for 30 min at room temperature. The insoluble materials were filtered off through a celite pad. The organic phase was dried over MgSO₄. After filtration, the solvent was evaporated under reduced pressure. The residue was purified by preparative TLC using silica gel as stationary phase and hexane as eluent, affording the desired product **4**.

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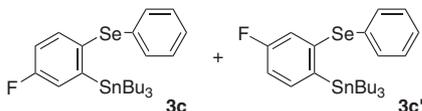
Characterization data



Tributyl[2-(phenylselanyl)phenyl]stannane (3a): Yield 97.1 mg (62%); light yellow oil; ^1H NMR (CDCl_3 , 300 MHz) δ : 7.52 (dd, J 7.5 Hz, J 1.3 Hz, 1H), 7.45 (dd, J 7.5 Hz, J 1.6 Hz, 1H), 7.30-7.13 (m, 7H), 1.55-1.44 (m, 6H), 1.27 (sext, J 7.3 Hz, 6H), 1.08-1.03 (m, 6H), 0.84 (t, J 7.3 Hz, 9H); ^{13}C NMR (CDCl_3 , 75 MHz) δ : 151.4, 139.2, 137.5, 135.8, 134.0, 130.5, 129.3, 129.1, 127.3, 126.3, 29.1, 27.4, 13.7, 11.2; IR (film) $\nu_{\text{max}}/\text{cm}^{-1}$: 2956, 2923, 1926, 1849, 1793, 1732, 1578, 1470, 1441, 1070, 736, 689; Elemental Analysis: calc. for $\text{C}_{24}\text{H}_{36}\text{SeSn}$: C 55.20; H 6.95%; found: C 55.20; H, 6.85%.

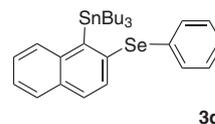


Tributyl[4,5-dimethyl-2-(phenylselanyl)phenyl]stannane (3b): Yield 99.0 mg (60%); light yellow oil; ^1H NMR (CDCl_3 , 500 MHz) δ : 7.25-7.13 (m, 7H), 2.26 (s, 3H), 2.23 (s, 3H), 1.52-1.42 (m, 6H), 1.25 (sext, J 3 Hz, 6H), 1.04-0.98 (m, 6H), 0.84 (t, J 3 Hz, 9H); ^{13}C NMR (CDCl_3 , 125 MHz) δ : 148.7, 140.3, 138.9, 138.1, 137.7, 137.0, 136.0, 129.6, 129.0, 125.8, 29.1, 27.4, 19.9, 19.2, 13.6, 11.1; IR (film) $\nu_{\text{max}}/\text{cm}^{-1}$: 2956, 2924, 1605, 1579, 1420, 1212, 843, 733, 689; Elemental Analysis: calc. for $\text{C}_{26}\text{H}_{40}\text{SeSn}$: C 56.75; H, 7.33%; found: C 56.60; H, 7.16%.

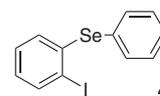


Mixture of tributyl[5-fluoro-2-(phenylselanyl)phenyl]stannane (3c) and tributyl[4-fluoro-2-(phenylselanyl)phenyl]stannane (3c'): yield 55.1 mg (34%); light yellow oil; ^1H NMR (CDCl_3 , 500 MHz) δ : 7.54 (dd, J 8.5 Hz, J 5.5 Hz, 1H), 7.43-7.37 (m, 0.5H), 7.36-7.32 (m, 1H), 7.28-7.22 (m, 1.5 H), 7.21-7.13 (m, 6.5H), 6.97-6.95 (m, 0.5H), 6.94-6.90 (m, 1H), 1.54-1.44 (m, 9H), 1.27 (sext, J 7.5 Hz, 6H), 1.26 (sext, J 7.5 Hz, 3H), 1.12-1.03 (m, 9H), 0.86 (t,

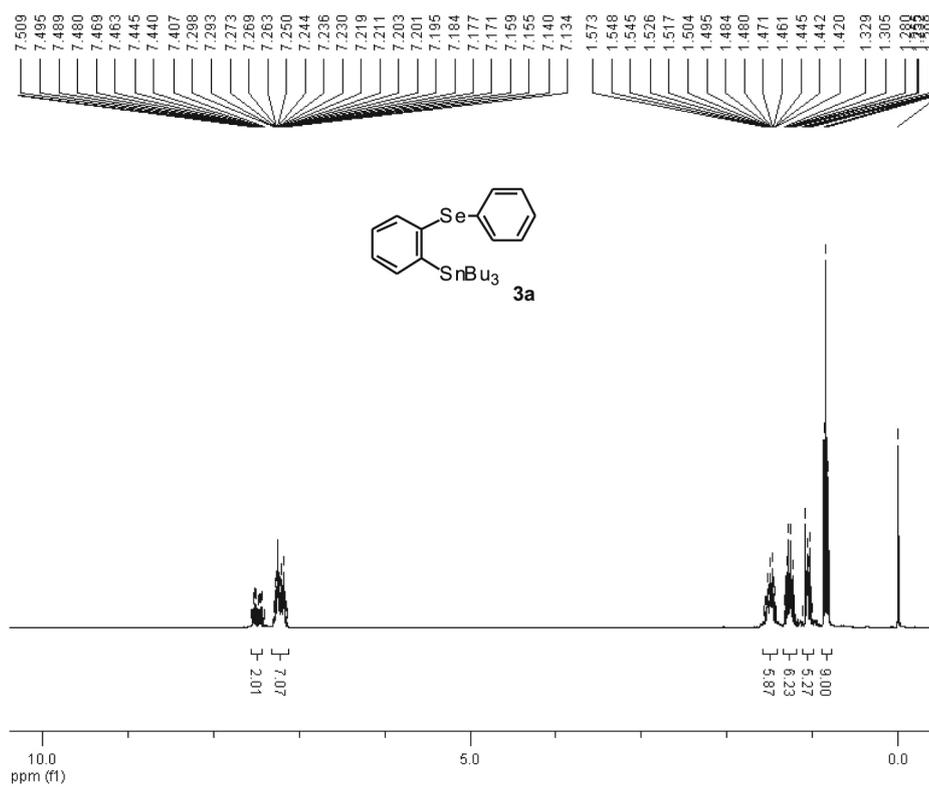
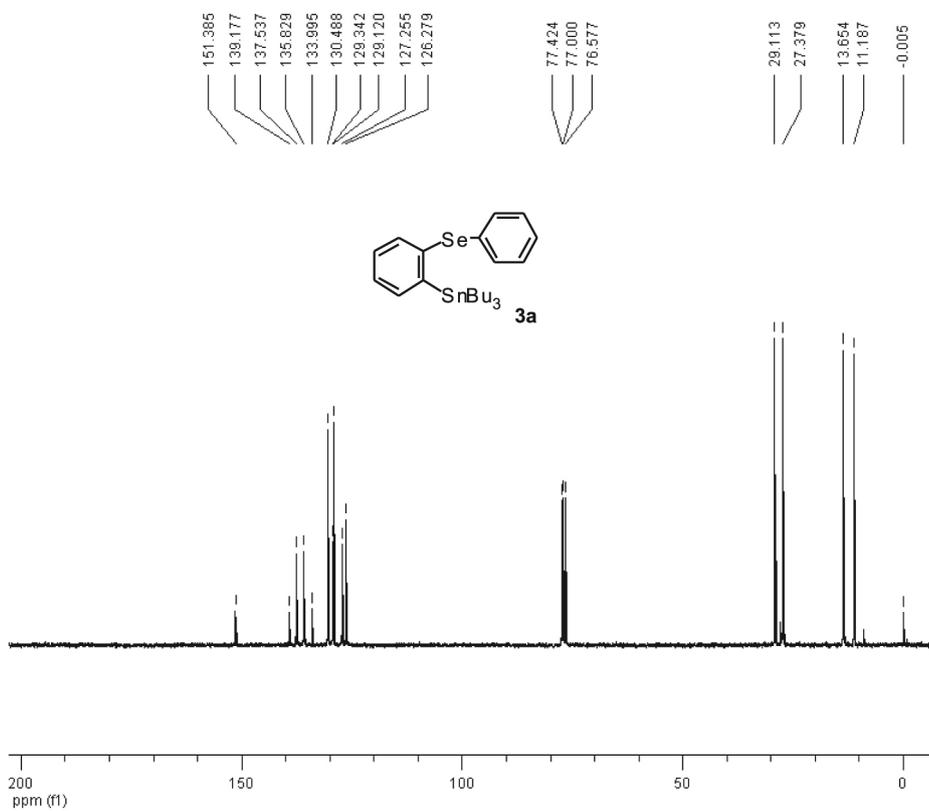
J 7.5 Hz, 9H), 0.84 (t, J 7.5 Hz, 4.5H); ^{13}C NMR (CDCl_3 , 125 MHz) δ : 163.4 (d, J 248 Hz), 162.5 (d, J 250 Hz), 155.6 (d, J 2 Hz), 141.3 (d, J 6Hz), 138.4 (d, J 7Hz), 138.2 (d, J 7 Hz), 136.0, 134.3, 133.0 (d, J 3 Hz), 131.8, 129.7, 194.4 129.2, 127.6, 127.1, 125.2, 123.9 (d, J 18 Hz), 121.3 (d, J 20 Hz), 116.6 (d, J 22 Hz), 114.4 (d, J 19 Hz), 29.1, 29.0, 27.3, 13.6, 11.3, 11.2; ^{77}Se RMN (CDCl_3 , 95 MHz) δ : 437.2, 437.1; IR (film) $\nu_{\text{max}}/\text{cm}^{-1}$: 2956, 2926, 1942, 1882, 1735, 1568, 1455, 1091, 845, 733, 689; Elemental Analysis: calc. for $\text{C}_{24}\text{H}_{35}\text{FSeSn}$: C 53.36; H, 6.53%; found: C 53.06; H, 6.31%.

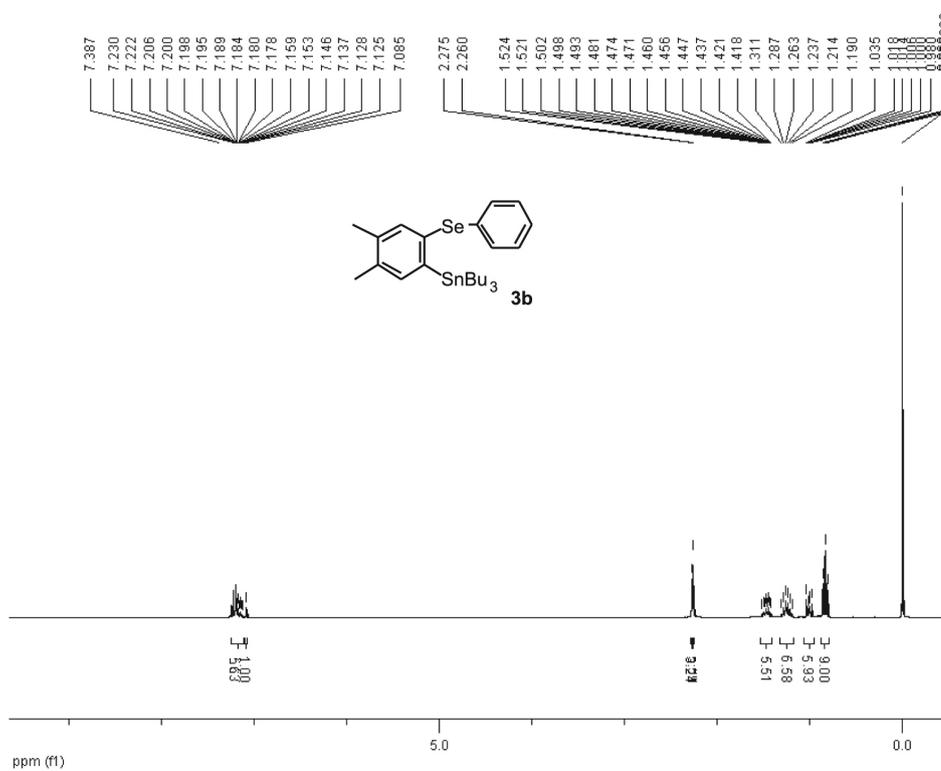
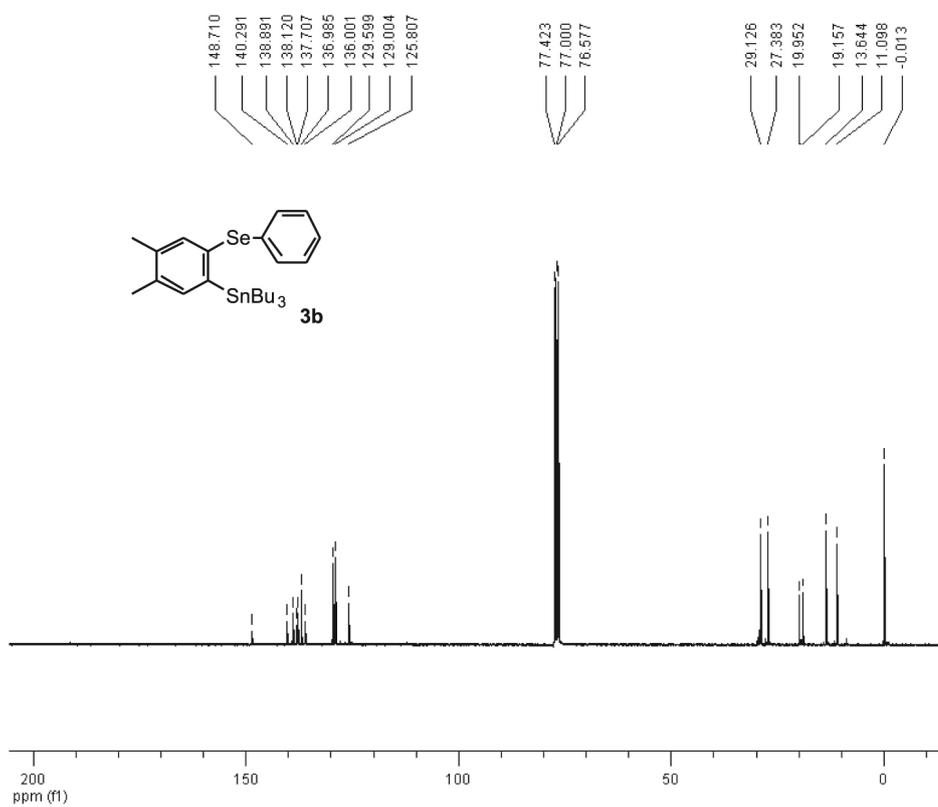


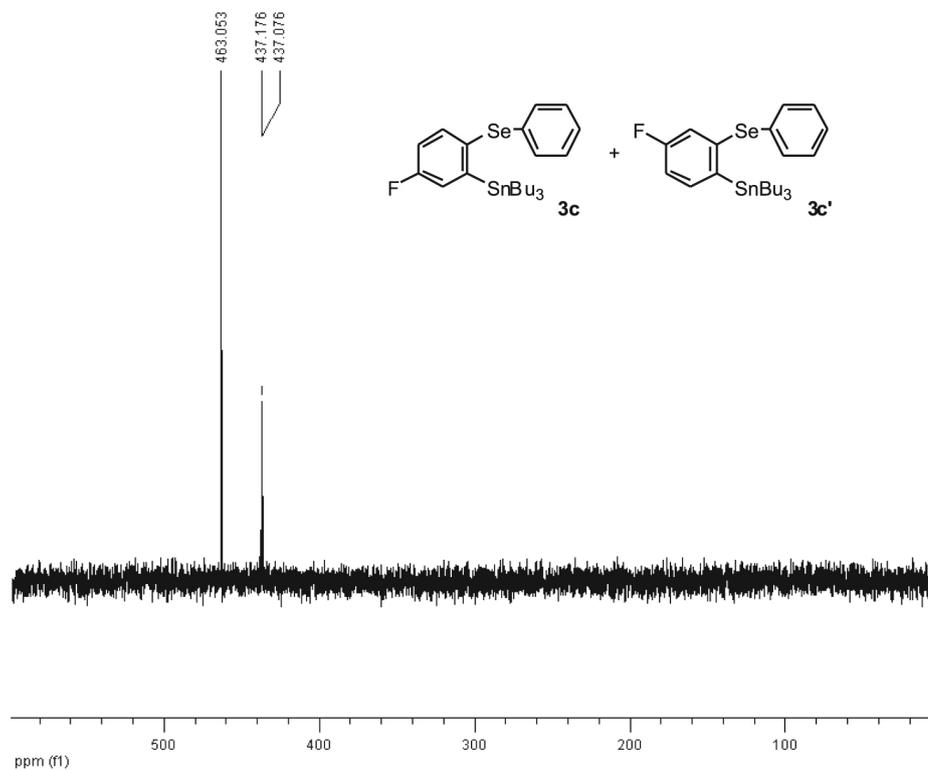
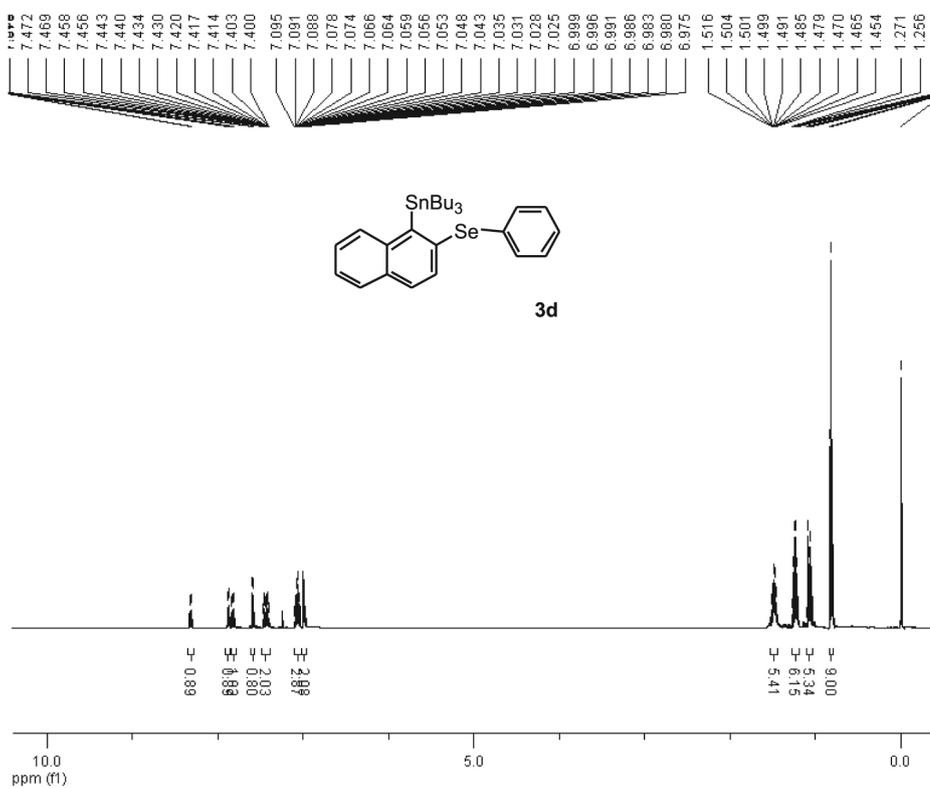
Tributyl[2-(phenylselanyl)naphthalen-1-yl]stannane (3d): yield 94.4 mg (55%); light yellow oil; ^1H NMR (CDCl_3 , 500 MHz) δ : 8.27 (d, J 8.0 Hz, 1H), 7.83 (d, J 8.0 Hz, 1H), 7.77 (d, J 8.0 Hz, 1H), 7.54 (d, J 8.0 Hz, 1H), 7.43-7.36 (m, 2H), 7.05-6.98 (m, 3H), 6.99-6.93 (m, 2H), 1.47-1.40 (m, 6H), 1.19 (sext, J 7.5 Hz, 6H), 1.08-0.97 (m, 6H), 0.77 (t, J 7.5 Hz, 9H); ^{13}C NMR (CDCl_3 , 125 MHz) δ : 155.7, 136.8, 135.5, 134.6, 134.3, 133.5, 129.2, 129.0, 128.9, 128.5, 127.9, 127.1, 126.3, 125.3, 29.1, 27.4, 13.6, 11.7; ^{77}Se RMN (CDCl_3 , 95 MHz) δ : 383.3; IR (film) $\nu_{\text{max}}/\text{cm}^{-1}$: 2955, 2923, 1933, 1851, 1794, 1733, 1578, 1476, 1069, 1019, 702, 689; Elemental Analysis: calc. for $\text{C}_{28}\text{H}_{38}\text{SeSn}$: C 58.77; H 6.69%; found: C 58.43; H, 7.02%.



(2-Iodophenyl)(phenyl)selenide (4) (CAS Number 363617-27-0): yield 21.6 mg (67%); white solid; mp 76-78 °C (Lit.⁸ mp 73-74 °C); ^1H NMR (CDCl_3 , 300 MHz) δ : 7.76 (dd, J 7.5 Hz, J 1.2 Hz, 1H), 7.66-7.61 (m, 2H), 7.45-7.35 (m, 3H), 7.12 (dd, J 7.5 Hz, J 1.5 Hz, 1H), 6.90-6.83 (m, 2H); ^{13}C NMR (CDCl_3 , 75 MHz) δ : 140.6; 139.4, 135.8, 130.2, 129.8, 128.8, 128.7, 127.4, 99.4; IR (KBr) $\nu_{\text{max}}/\text{cm}^{-1}$: 1949, 1877, 1436, 999, 741, 687; LRMS (m/z , %): $[\text{M}+1]^+$ 360 (11), 232 (28), 152 (100), 116 (70), 77 (54), 51 (93), 50 (87).

Copies of ^1H and ^{13}C NMR spectraFigure S1. ^1H NMR for compound **3a**.Figure S2. ^{13}C NMR for compound **3a**.

Figure S3. ¹H NMR for compound **3b**.Figure S4. ¹³C NMR for compound **3b**.

Figure S7. ^{77}Se NMR for mixture of compounds **3c** and **3c'**.Figure S8. ^1H NMR for compound **3d**.

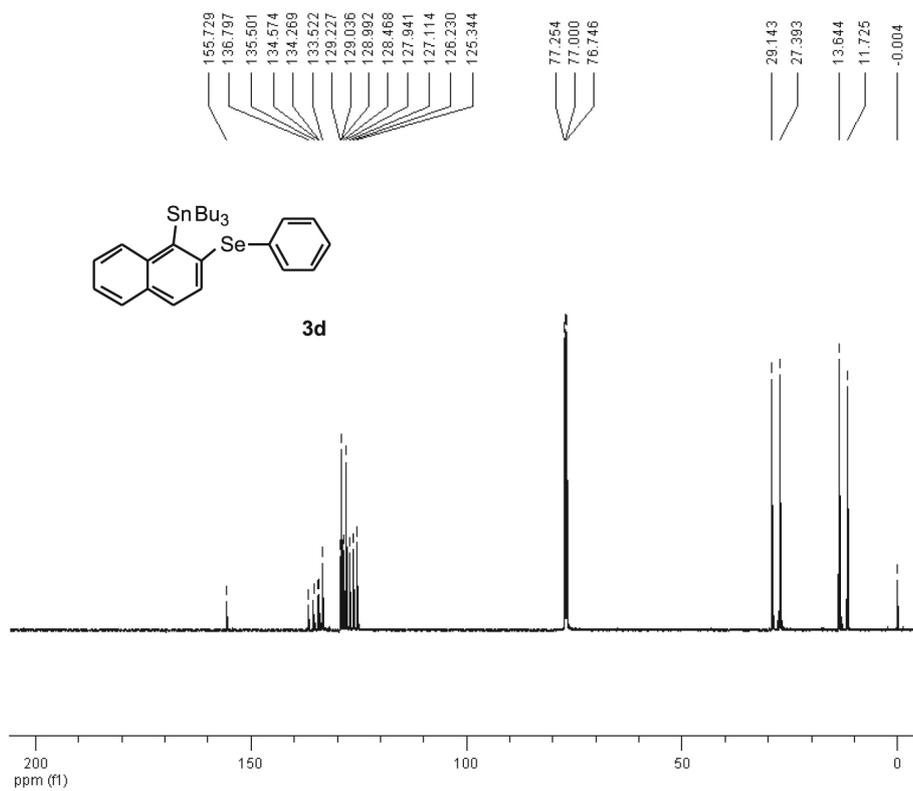


Figure S9. ^{13}C NMR for compound **3d**.

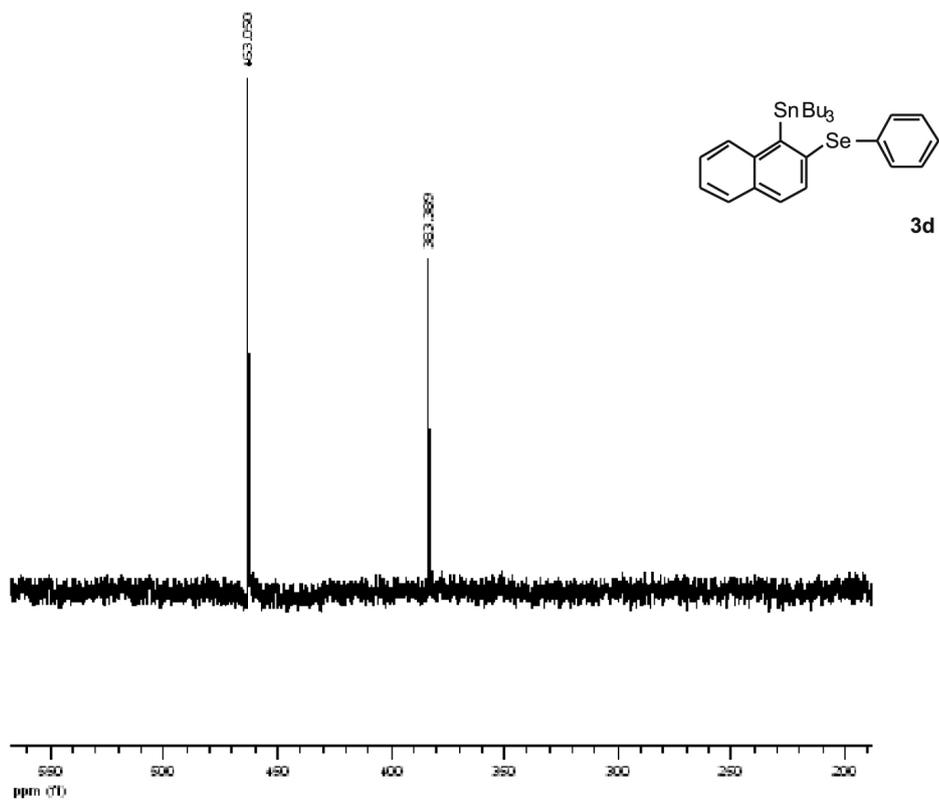


Figure S10. ^{77}Se NMR for compound **3d**.

References

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