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Exclusive selectivity in the one-pot formation of C–C and C–Se bonds involving Ni-catalyzed alkynes hydroselenation: Optimization of the synthetic procedure and a mechanistic study

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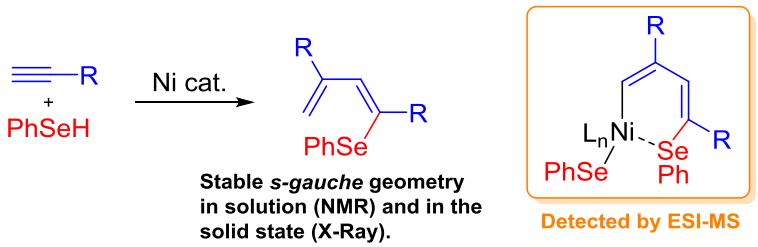


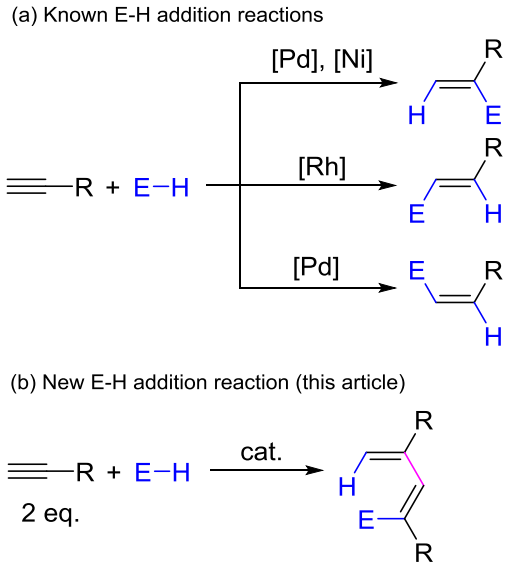
Abstract: A unique Ni-catalyzed transformation is reported for the one-pot highly selective synthesis of previously unknown mono-selenosubstituted 1,3-dienes starting from easily available terminal alkynes and benzeneselenol. The combination of a readily available catalyst precursor, $Ni(acac)_2$, and an appropriately tuned phosphine ligand, PPh_2Cy, resulted in the exclusive assembly of *s-gauche* diene skeleton *via* the selective formation of C–C and C–Se bonds. The unusual diene products were stable under regular experimental conditions, and the products maintained *s-gauche* geometry both in the solid state and in solution, as confirmed by X-ray analysis and NMR spectroscopy. Thorough mechanistic studies using ESI-MS revealed the key Ni-containing species involved in the reaction.

Keywords: catalysis, Ni, mechanism, dienes, hydroselenation.

1. Introduction

The increasing complexity of molecular architectures, as demanded in organic synthesis and materials science, has led to the development of powerful tools to create new C–C and C–heteroatom (C–E) bonds with high selectivity in the specific framework of a polyfunctional molecule. Transition-metal-catalyzed transformations have significantly changed this area of selective organic synthesis, offering a number of outstanding synthetic approaches.[1,2,3] Great practical importance has been demonstrated in the large number of total syntheses of pharmaceuticals, biologically active compounds and a new generation of functional materials that are hardly accessible by other methods.[1-3]

A highly efficient catalytic approach for the synthesis of functionalized alkenes involves the addition reactions of various heteroatom-hydrogen bonds (E–H) to alkynes (Scheme 1). The transformation is atom-economic by intrinsic design, and it can be coupled with transition metal catalysis to achieve thorough selectivity control. Within this approach, various highly efficient catalytic systems leading to the formation of new C–E bonds have been developed. The incorporation of C–N,[4,5] C–O,[4] C–P,[4,6,7] C–S,[4,8,9] C–Se,[4,8,9] C–I[10] and other C–E bonds[11] into organic molecules using transition-metal catalysis is now a common practice.



Scheme 1. Atom-economic procedures *via* the catalytic addition of E–H bonds to alkynes: (a) – the synthesis of alkenes; (b) – the one-pot formation of C–C and C–E bonds in the synthesis of dienes.

It is important to note that even sulfur and selenium compounds, which have long been considered catalyst poisons, are now routinely involved in metal-catalyzed transformations to

access various organic chalcogenides.[4,8,9,12] The regio- and stereoselectivity of the addition process can be tuned by selection of the transition metal catalyst (Scheme 1).[13,14] Many catalytic systems have been developed for the preparation of Markovnikov-type (branched) products,[15,8,9] as well as anti-Markovnikov (linear) products with *cis*-geometry[16,8,9] and *trans*-geometry.[17,8,9]

One-pot transformations involving two molecules of an alkyne in the addition reaction remain a more challenging goal in the synthesis of organochalcogen derivatives. In such a case, the one-pot formation of C–C and C–E bonds leads to the construction of a diene skeleton with a predefined position of the functional group. As a related processes, a few examples of such catalytic transformations were demonstrated for E–E (E=S, Se) additions starting from diaryldichalcogenides and terminal alkynes and furnishing bis-functionalyzed dienes in one step.[18,19,20] However, synthesis of dienes *via* the addition of E–H bond remained unexplored.

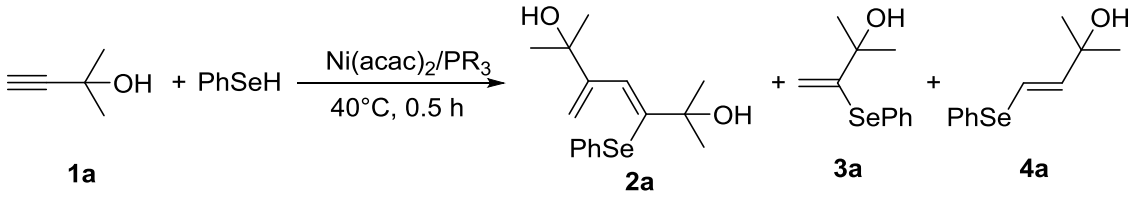
In the present study, we report such a new reaction to access selenium-functionalized diene products involving E–H bond addition reaction (Scheme 1b; E = Se). The Ni-catalyzed transformation constitutes the development of a highly stereo- and regioselective catalytic system to obtain previously unknown Se-substituted 1,3-dienes. This three-component reaction involving two molecules of the alkyne and one molecule of the benzeneselenol is a unique transformation that combines the advantages of atom-economic additions and one-pot transformations. The synthesis of substituted functionalized dienes with a predetermined configuration is of great demand due to their importance as building blocks in organic synthesis, Diels-Alder reactions, and polymer chemistry.[21,22]

In the present article, we describe a practical procedure for the one-pot preparation of mono-functionalized dienes *via* the addition reaction of benzeneselenol to alkynes. A mechanistic study, carried out with ESI-MS, NMR and X-Ray methods, revealed the structure of products and intermediate metal complexes involved in the catalytic transformation.

2. Results and discussion

2.1 Rendering a highly selective transformation towards the 1-PhSe-1,3-diene framework.

We have chosen the Ni-catalyzed reaction between 2-methyl-3-butyn-2-ol (**1a**) and phenylselenol as a model system to optimize the reaction conditions (Scheme 2). Both components of the reaction (the alkyne and PhSeH) gave clearly resolved signals in the NMR spectrum and allowed the reaction progress to be efficiently monitored. The readily available $Ni(acac)_2$ salt was chosen as a catalyst precursor to develop a cost-efficient practical procedure. We avoided to use $Ni(COD)_2$ since it is much more expensive and highly air/moisture sensitive compound.

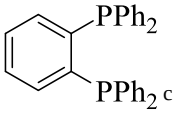


Scheme 2. The Ni-catalyzed model reaction of PhSeH with alkyne **1a**.

After stirring at 40°C for 30 min, phenylselenol was consumed by 87 % leading to the formation of alkene **3a** as the major product, diene **2a** as the minor product and alkene **4a** as the trace component (Entry 1, Table 1). It should be noted that the formation of diene **2** is a specific feature of Ni-catalyzed transformations taking into account that a similar reaction involving other transition metals (Pt, Pd and Rh) led only to the formation of alkenes. To utilize the unique opportunity provided by the Ni system, we have improved the performance of the catalytic reaction to promote the diene formation as the major product. The roles of the following factors were investigated: i) ligand effect; ii) catalyst loading effect; iii) influence of the PhSeH : alkyne ratio; iv) influence of the metal : ligand ratio; v) solvent effect; and vi) acid and base effect. Rigorous optimization of the reaction conditions was required in order to tune the transformation towards the diene **2a** as a major product. Below, we briefly consider the major findings required to create an efficient catalytic system.

Table 1. The ligand effect in the Ni-catalyzed reaction of PhSeH and alkyne **1a**.[a]

Entry	**Ligand (PR_3)**	**Conversion of the PhSeH, %** [b]	**2a : 3a : 4a products ratio** [b]
1	-	87	23:73:4
2	P(*i*-PrO)$_3$	97	17:28:55
3	CH_2=C(PPh_2)$_2$[c]	3	27:73:0
4	$PPhCy_2$	97	29:67:4
5	PPh_3	93	30:58:12
6	P(*p*-ClC_6H_4)$_3$	87	30:39:31
7	PCy_3	99	32:64:4
8	P(*p*-$MeOC_6H_4$)$_3$	98	37:53:10

9	 [c]	10	43:41:16
10	$CH_2(PPh_2)_2$ [c]	61	44:43:13
11	PPh_2Bn	97	47:32:21
12	PPh_2Et	98	49:33:18
13	$PPh_2(CH_2)_4PPh_2$ [c]	92	53:37:10
14	PPh_2Cy	95	53:38:9
15	PPh_2Me	98	56:30:14
16	$PPhMe_2$	12	73:27:0

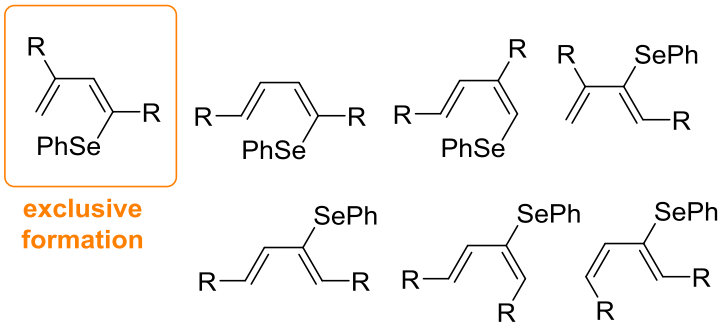
[a] 2 mol.% of $Ni(acac)_2$, PhSeH : alkyne = 1:4, $Ni(acac)_2$: PR_3 = 1:10, solvent free, 40°C, 0.5 h. [b] Determined by ^1H NMR spectroscopy of the crude reaction mixture. [c] 10 mol.% of the ligand was used.

At the first stage, various phosphine ligands were evaluated in the catalytic reaction (Table 1). Most of the ligands resulted in good PhSeH conversion (61-99 %); however, the selectivity of the reaction differed significantly depending on the structure of the ligand. Catalytic system with P(*i*-PrO)$_3$ ligand demonstrated high activity, but relatively poor selectivity for the formation of diene **2a** was found (Entry 2, Table 1). Phosphine ligands with bulky aryl and alkyl substituents have shown better performance (Entries 3-8, Table 1), increasing the selectivity of **2a** formation up to 37 % in the case of arylphosphine with an electron-donating *p*-methoxy substituent (Entry 8, Table 1). The selectivity of the diene **2a** formation was further improved up to 53 % using bidentate phosphines (Entries 9, 10, 13; Table 1) and up to 56 % using alkyldiphenylphosphines (Entries 11, 12, 14, 15; Table 1). The presence of one alkyl substituent in the arylphosphine ligand seems to be crucial for reaction selectivity (*cf.* Entries 4, 5 and 14; Table 1). Because substituents such as Me and Cy showed comparable results (*cf.* Entries 14 and 15; Table 1), we may suppose that the electronic factors of the ligands prevail over the steric factors with respect to achieving a highly selective catalytic system for the formation of diene **2a**. This is in agreement with the fact that $PPhMe_2$ was the most selective ligand, giving diene **2a** with 73 % selectivity (Entry 16, Table 1).

A practical evaluation of the scope of this catalytic reaction indicated that the PPh_xMe_y ligands were disadvantaged, because of quick oxidation during the reaction leading to the degradation of active catalytic species. As a result of this evaluation, PPh_2Cy was chosen as the ligand of choice for further optimization of the catalytic system.

It should be emphasized that in the developed reaction, only one type of diene was formed

upon the several structural frameworks potentially accessible through the addition reaction (Scheme 3). Such exclusive selectivity in the assembly of diene skeleton is an important feature of the developed catalytic system. The result is in sharp contrast with previously reported findings on Ni-catalyzed reactions, where mixtures of dienes or higher oligomers were observed in significant amounts.[18,20]



Scheme 3. Possible 1,3-diene frameworks accessible *via* the reaction of two molecules of an alkyne with PhSeH.

In the next stage, the catalyst loading was varied in the studied catalytic system. The amounts of $Ni(acac)_2$ were changed in the range of 0.5, 2.0 and 5.0 mol.%, while the ratio of $Ni(acac)_2$: PPh_2Cy was kept constant. As little as 0.5 mol.% of the catalyst precursor provided a quantitative conversion of the PhSeH and diene : alkenes ratio as **2a** : (**3a**+**4a**) = 50 : 50. Upon usage 2 mol.% of $Ni(acac)_2$ the selectivity was slightly improved to 53:47, while further increasing the catalyst loading to 5 mol.% resulted in a significant drop of the selectivity to 33 : 67. Thus, 2 mol.% of the catalyst precursor was found to be an optimal catalyst loading amount.

Next, the influence of the PhSeH : alkyne ratio on the selectivity of diene formation was investigated. In all cases, high values of PhSeH conversion were observed (Table 2). However, the measured diene : alkenes ratio was strongly dependent on the quantity of the alkyne. Increasing an excess of the alkyne led to higher yields of diene **2a** over the alkenes (Table 2, method A). Further improvement of the reaction selectivity was achieved by the dropwise addition of PhSeH to the reaction mixture (Table 2, method B). Indeed, the dropwise addition of PhSeH yielded significant quantities of an excess of alkyne during the reaction and improved selectivity. The observed selectivity of diene **2a** formation reached the value **2a** : (**3a**+**4a**) = 82 : 18 (Entry 3; Table 2, method B). To render a selective transformation, the PhSeH : alkyne ratio of 1 : 4 was chosen as an optimal value since further increase of the amount of alkyne only slightly influenced the selectivity, but decreased the conversion (*cf.* Entries 3, 4; Table 2, method B).

Table 2. The influence of the PhSeH: alkyne ratio on the yield and selectivity of the Ni-catalyzed reaction of PhSeH with alkyne **1a**.[a]

Entry	PhSeH : alkyne	Conversion, % (2a:3a:4a ratio)[b]	
		method A[c]	method B[c]
1	1:2	91 (41:52:7)	95 (58:34:8)
2	1:3	91 (48:46:6)	96 (69:24:7)
3	1:4	95 (53:38:9)	93 (82:11:7)
4	1:5	90 (58:35:7)	89 (84:12:4)

[a] 2 mol.% $Ni(acac)_2$, 20 mol.% PPh_2Cy, 40°C, 0.5 h. [b] Determined by ^1H NMR spectroscopy of the crude reaction mixture. [c] Method A: single portion addition of PhSeH; method B: dropwise addition of PhSeH during the reaction.

To avoid catalyst deactivation during the reaction, which involves precipitation of metal-chalcogen species, it is critical to determine a reliable ratio of $Ni(acac)_2$: PPh_2Cy. Previous studies of Pd- and Ni-catalyzed C–Se bond formation *via* addition reactions noted that larger amounts of phosphine ligand may be required.[8] In the studied reaction, a ratio of $Ni(acac)_2/PPh_2Cy$ = 1 : 2 was sufficient to achieve the full conversion of PhSeH, and diene **2a** was formed with 76 % selectivity under dropwise addition conditions. Increasing the $Ni(acac)_2$: ligand ratio to 1 : 5 and 1 : 10 did not effect the conversion, while the selectivity of the formation of diene **2a** was improved to 80 and 82 %, respectively. Thus, for practical reasons, the $Ni(acac)_2$: PPh_2Cy ratio of 1 : 2 should be sufficient to carry out the reaction with good selectivity. It is interesting to note that even significant excess quantities of the phosphine ligand did not block the catalytic reaction and slightly increased selectivity.

The solvents noticeably influenced the outcome of the studied reaction (Table 3). When the reaction was performed in THF, slightly better selectivity was observed, compared to solvent-free conditions (*cf.* Entries 1 and 2; Table 3). DMF, MeOH and MeCN showed lower selectivity for the diene formation (Entries 3-5; Table 3). Methylene chloride and toluene significantly improved the selectivity for the formation of diene **2a** (Entries 6 and 7; Table 3). In both cases, the selectivity of diene formation reached the value of **2a** : (**3a**+**4a**) = 70 : 30. Toluene was chosen to develop the synthetic procedures and to avoid Cl-containing solvents for environmental protection reasons. Carrying out the reaction in toluene with the dropwise addition of PhSeH led to the formation of diene **2a** with 80 % selectivity and quantitative conversion of PhSeH (Entry 8; Table 3).

Table 3. The effect of solvent in Ni-catalyzed reaction of PhSeH with alkyne **1a**.[a]

Entry	Solvent	PhSeH conversion, % (Ratio 2a:3a:4a)[b]
1	-	95 (53:38:9)
2	THF	91 (55:41:4)
3	DMF	92 (37:56:7)
4	MeOH	90 (40:55:5)
5	MeCN	94 (44:47:9)
6	CH_2Cl_2	91 (70:26:4)
7	Toluene	92 (70:27:3)
8	Toluene	98 (80:17:3)[c]
9	Toluene	98 (94:3:3)[c,d]

[a] PhSeH : alkyne = 1:4, single portion addition of PhSeH, 2 mol.% $Ni(acac)_2$, 20 mol.% PPh_2Cy, 40°C, 0.5 h., and 0.2 ml of solvent. [b] Determined by ^1H NMR spectroscopy of the crude reaction mixture. [c] With the dropwise addition of PhSeH in the Entries 8,9 (without the dropwise addition of PhSeH in the Entries 1-7). [d] In the presence of 10 mol.% of Et_3N.

Previously, it was reported that the addition of catalytic amounts of acid or base can significantly influence the activity and selectivity of the catalytic systems.[8,9] In the present study, we have shown that the addition of 10 mol.% of Et_3N to the catalytic system increased the diene/alkenes selectivity to 94:6 (Entry 9, Table 3). When the amount of the additive was increased to 1 equivalent, significantly lower conversions were observed without improving the overall selectivity.

As an overall progress of the optimization procedure: starting with a conversion of 87 % and selectivity of 23 : 77 (Entry 1, Table 1), we were able to render a highly selective synthesis of the desired 1-PhSe-1,3-diene framework with 98 % conversion and 94 : 6 selectivity (Entry 9, Table 3). It should be emphasized that the direction of the addition reaction was changed to form the diene as the major product (94 : 6) instead of the alkenes (23 : 77).

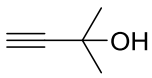
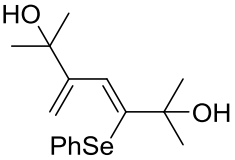
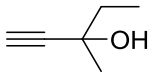
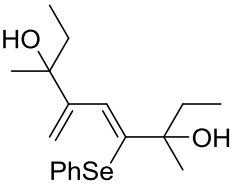
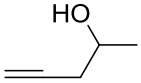
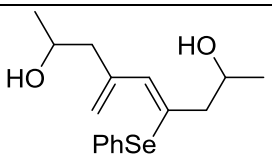
2.2 Optimal synthetic procedure and the scope of the catalytic reaction.

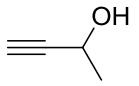
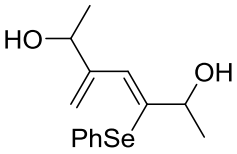
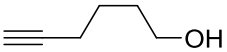
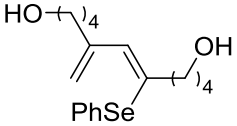
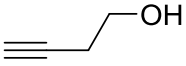
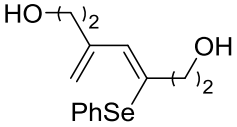
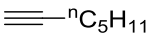
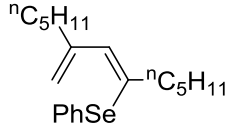
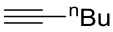
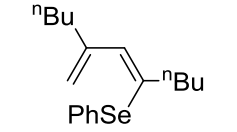
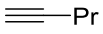
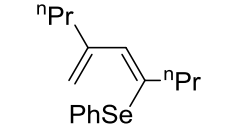
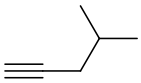
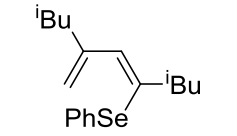
Using the optimized synthetic procedure, the scope of the catalytic reaction was studied for

various terminal alkynes (Table 4). The highest selectivity was observed for alkynes bearing an OH-group without an allylic hydrogen atom resulting in the 86 % and 80 % yields, respectively (Entries 1, 3; Table 4). In most of the studied cases, good to moderate product yields were found (Entries 4-11; Table 4). Phenylacetylene, as an alkyne bearing aromatic substituent, was successfully involved in the catalytic reaction, however the corresponding vinyl selenides **3** and **4** were the major products (**2** : **3**+**4** = 36 : 64, 89% yield). Amazingly, we have found that the reaction may be performed under phosphine-free conditions in the presence of Et_3N only. In a few cases, the selectivity and yields of the phosphine-free system were close to that of the system with the phosphine ligands (*cf.* Entries 1 and 2; Table 4) or yielded even higher values (Entry 5, Table 4).

For the purpose of a synthetic method, we have addressed the possibility of scaling up the catalytic procedure. Using 5 mmol of PhSeH under the optimized reaction conditions, dienes **2a** and **2i** were obtained with the yields of 78 % (1.49 g) and 62 % (0.94 g), respectively. It should be mentioned that the yield in a gram-scaled experiment in the case of hexyne-1 was by 13 % larger, compared to the yield obtained on the scale of 0.5 mmol (Entry 9, Table 4). The products were purified by column chromatography and the structures were confirmed by ^{1}H, ^{13}C, ^{77}Se, 2D COSY and 2D NOESY NMR experiments.

Table 4. Scope of the developed catalytic system and the yields of dienes **2**.[a]

Entry	Alkyne	T, °C/ time, h	Diene	Conversion of 2, % (yield, %) [b]
1	 **1a**	40/ 0.5	 **2a**	92 (86) 90 (78)[e]
2				76 (69)[c]
3	 **1b**	40/ 1.5	 **2b**	84 (80)[d]
4	 **1c**	30/ 1.5	 **2c**	77 (58)[d]

5	 **1d**	r.t./ 1.5	 **2d**	67 (51) [c, d]
6	 **1e**	r.t./ 1.5	 **2e**	54 (46)
7	 **1f**	r.t./ 2	 **2f**	52 (42)
8	 **1g**	40/ 1.5	 **2g**	56 (50)
9	 **1h**	r.t./ 2	 **2h**	64 (49) 76 (62)[e]
10	 **1i**	40/ 1.5	 **2i**	57 (44)
11	 **1j**	r.t./ 1.5	 **2j**	57 (52) [f]

[a] Toluene, PhSeH : alkyne = 1:4, dropwise addition of PhSeH, 2 mol.% $Ni(acac)_2$, 20 mol.% PPh_2Cy, and 10 mol.% Et_3N. [b] Conversion was determined by ^1H NMR spectroscopy of the crude reaction mixture; the yield of the isolated product after column chromatography is given in parenthesis. [c] Reaction was performed without PPh_2Cy in the catalytic system containing $Ni(acac)_2$/ Et_3N (see experimental part). [d] The equimolar mixture of diastereomeric dienes was formed in the case of alkynes possessing chiral centers. [e] Gram-scaled experiments with 5 mmol of the benzeneselenol (see text). [f] The product contained alkene **3j** as a contaminant (20%).

The *s-gauche* conformation of diene **2a** in solution was evident from the 2D NOESY experiment (Figure S1). The structure of the synthesized diene in a crystal was unambiguously confirmed by the X-ray analysis of **2a** (Figure S3). X-ray analysis revealed the unique geometry of the synthesized diene, which preserved *s-gauche* conformation with the value of the dihedral angle C(1)-C(2)-C(3)-C(4) = 24.66°. In contrast, 1,3-dienes are typically expected to hold the *s-trans* conformation. To clarify the possibility of the existence of an *s-trans* conformer, DFT calculations were performed at the ωB97X-D/6-311G(d) level for the diene **2a**. The obtained results demonstrated that the formation of s-*trans* conformer is unfavorable for such dienes (no energy minimum was localized), thus the *s-gauche* form is the only stable conformer, which is in excellent agreement with the experimental results.

2.3 Mechanistic study of the catalytic reaction.

A highly selective transformation toward only one type of diene framework (Scheme 3) and the formation of the unusual *s-gauche* diene geometry is an interesting feature of the developed catalytic transformation. A detailed mechanistic investigation of the developed catalytic reaction was performed using a combination of ESI-MS/MS and ESI-MS methods. Electrospray ionization (ESI) has several well-known advantages for liquid-phase mechanistic studies.[23,24,25] This method deals with solutions and allows the solutions to be easily and quickly monitored (both off-line and on-line) with minimal or no sample pretreatment. It is important to note that ionization occurs under gentle conditions at atmospheric pressure and leads to the formation of a gas-phase singly and/or multiply charged ions from primarily intact neutral species (reagents, intermediates, products). In the case of dissolved species that are initially charged (charged metal complexes, etc.), ESI may simply serve as a "bridge" for transferring the compounds from the liquid reaction media to the mass analyzer and detector without additional perturbation. The "soft" ES ionization, together with accurate mass measurements, provides valuable insight into the intermediates and mechanisms of catalytic reactions.[23-25] The tandem version of this technique, ESI-MS/MS, is an important tool for obtaining information about the structure of the analyzed compounds by means of collision-induced dissociation (CID).[26] Furthermore, it should be noted that the fragmentation pathways of selected ions at various collision energies address the questions about possible transformations and the strength of bonding within molecular fragments.

The reaction between **1a** (R' = CMe_2OH) and PhSeH (added dropwise) in methanol using $Ni(acac)_2/P(i\text{-}PrO)_3$ catalytic system was chosen for study by ESI-(+MS). The $P(i\text{-}PrO)_3$ ligand was selected for two reasons: i) the ligand is preferable for the mechanistic study, because it delivers

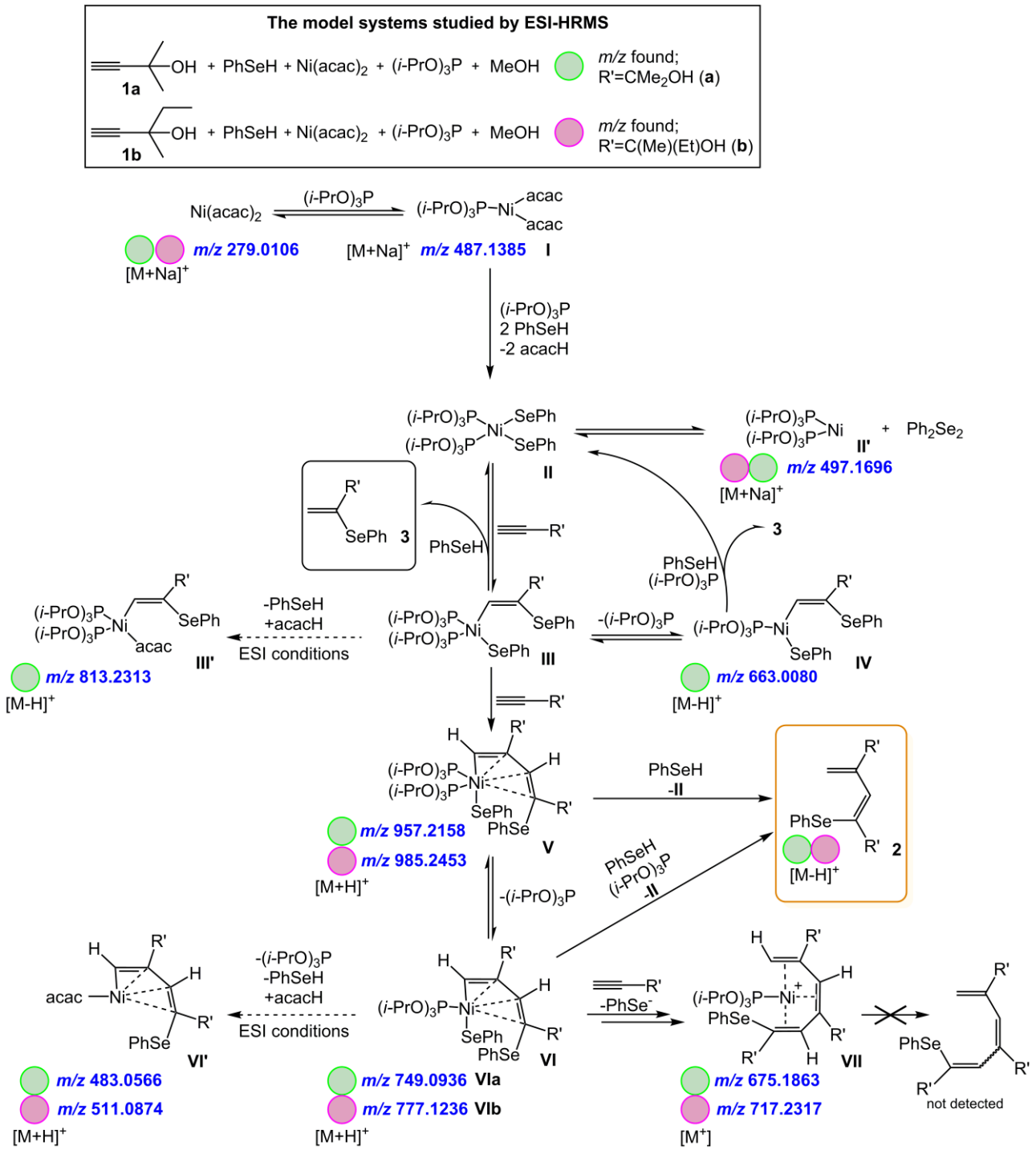
signals with higher intensity in the mass spectrum;[27] and ii) high conversion and formation of both types of products was observed (Entry 2; Table 1). The reaction was conducted for 10 min to reach partial conversion (confirmed by ^{1}H NMR). Aliquots were taken directly from the reaction mixture and immediately injected into the ESI ion source (see experimental part for details).

For unambiguous MS data interpretation, an independent catalytic reaction involving homologous alkyne – 3-methylpentyn-3-ol (**1b**) was studied by ESI-(+MS) in exactly the same manner as described above for **1a**. The difference between the alkynes **1a** and **1b** is equivalent to a single CH_2 group, thus this exact molecular mass difference simplified the analysis of spectral data.

The mass-spectra were registered and analyzed for both model systems, composed of the two independent reactions of PhSeH with the alkynes 2-methylbut-3-yn-2-ol (**1a**, R'=CMe_2OH) and 3-methylpent-1-yn-3-ol (**1b**, R'=C(Me)(Et)OH). Unexpectedly, no signals of complex **II** were detected in the mass-spectra of the catalytic reactions studied. Instead, the signals of the preceding complex with one coordinated P(*i*-PrO)$_3$ ligand (**I**) were observed in the mass spectra for simplified model system consisting of Ni(acac)$_2$ and P(*i*-PrO)$_3$ only (Scheme 4). Surprisingly, the Ni(acac)$_2$ signal was clearly observed in all studied systems with a good intensity.[28] A number of species, **II', III'** – **VI**, corresponding to the reaction of interest were successfully detected by ESI-(+MS). Performed ESI-MS study made it possible to propose a plausible mechanism of the catalytic reaction (Scheme 4). Within the studied mechanism, we can suppose that the protonolysis of complexes **III** and **IV** with PhSeH results in the formation of undesired alkene **3**.

The representative experimental and calculated mass spectra of the key intermediate **VIa** are shown below (Figure 1). Unequivocal identification of the Ni complex was facilitated by the unique isotopic distributions of selenium and nickel. A similar data were obtained for the other Ni complexes discussed in the present study.

The formation of a diene skeleton deserves a special note. Due to the presence of a Ni–C bond, complex **III** undergoes the insertion of the second alkyne molecule, giving complex **V**. Dissociation of the P(*i*-PrO)$_3$ ligand was observed to mediate the formation of complex **VI** (see Figure 3 for representative fragment **VIa**). Protonolysis of both complexes **V** and **VI** leads to the desired mono-selenosubstituted diene **2** with the regeneration of **II** (Scheme 4).



Scheme 4. ESI-(+MS) study of the mechanism of the Ni-catalyzed interaction of PhSeH with **1a** and **1b** (a green dot denotes the compounds detected in the reaction with alkyne **1a**; a pink dot with alkyne **1b**).

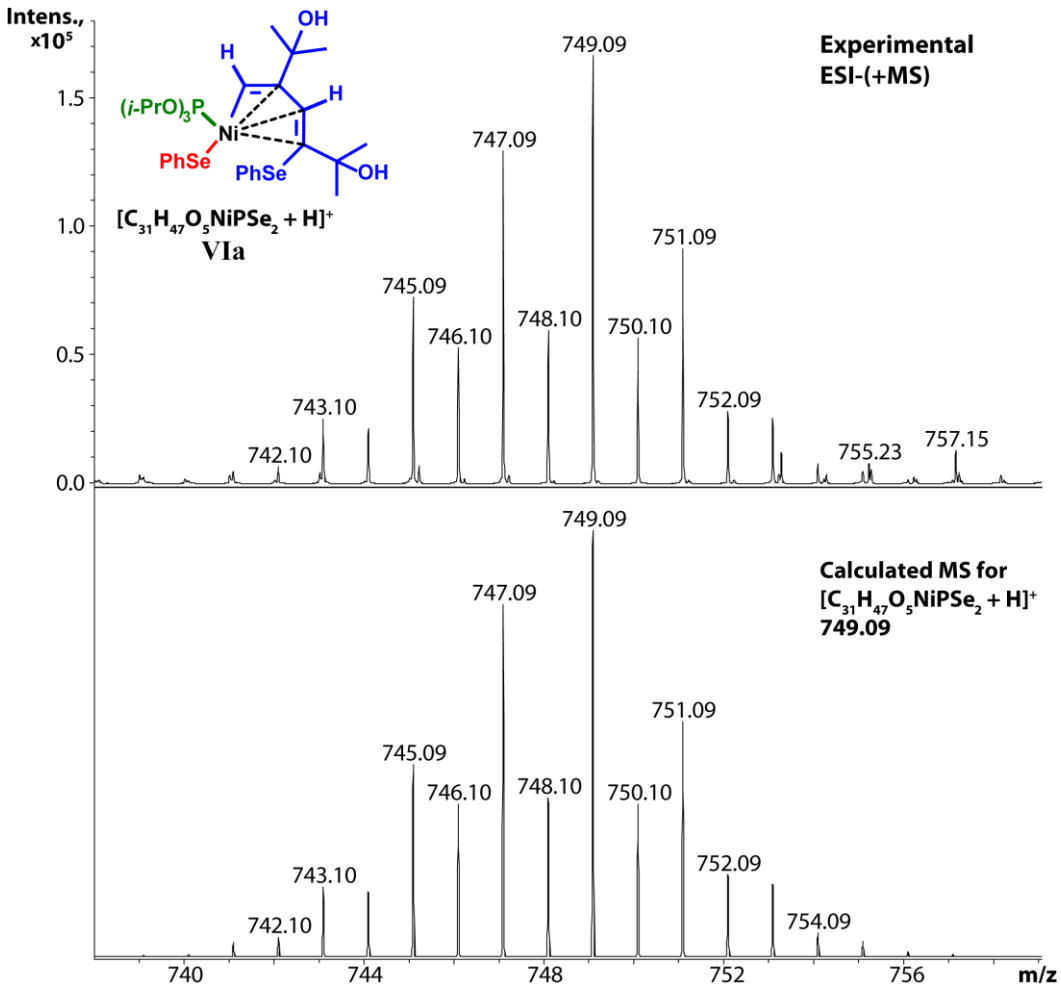


Figure 1. The experimentally measured (top) and calculated (bottom) ESI-(+MS) spectra of the Ni complex **VIa** showing the specific isotopic patterns (here and later the intensities of the signals are given in arbitrary units).

Upon analysis of the spectral data, the nickel complex **VII** containing three alkyne moieties and one PhSe group was also observed in the ESI-(+MS) spectra (Scheme 4). Most likely, complex **VII** is a result of the third alkyne molecule insertion into the Ni–C bond of **VI**, accompanied with elimination of the PhSe fragment (presumably during electrospraying). Although the protonolysis of **VII** may lead to a mono-selenosubstituted triene, we did not detect such species, neither in ESI-(+MS) nor in ^{1}H NMR spectra. Nickel complexes are known to catalyze olygomerization of alkynes,[29] however no feasible contribution of this side-reaction to the formation of soluble products was observed experimentally in the developed catalytic system. Oligomerization may still be involved as a side-reaction, but leading to formation of insoluble species.

Complexes **III'** and **VI'**, containing the acac moiety, were also observed in the mass spectra. As shown above, $Ni(acac)_2$ was formed directly inside the ESI ion source from a Ni^{2+} cation and acacH.[28] We suggest that **III'** and **VI'** were formed from acacH and complexes **III** and **VI**,

respectively, in similar way under ESI conditions (Scheme 4).

It is important to note that in the case of the ESI-(+MS) experiment for the reaction of PhSeH with **1b** (R' = C(Me)(Et)OH), the signals of all intermediates resulted from the insertion of a second alkyne molecule (complexes **V** and **VI**), were shifted to the higher mass region exactly on 28 Da (two CH_2 moieties) compared to those for 2-methylbut-3-yn-2-ol (R'=CMe_2OH). The representative mass spectra exhibiting shifts of 28 Da for **VI** are shown in Figure 2. The signal of complex **VII** resulted from insertion of the third alkyne molecule, causing a shift to the higher mass region of 42 Da (three CH_2 moieties). It should be noted that complexes **V** and **VI** led to the desired formation of diene **2** after protonolysis with PhSeH (Scheme 4), with their presence being independently confirmed by ESI-(+MS) for both alkynes.

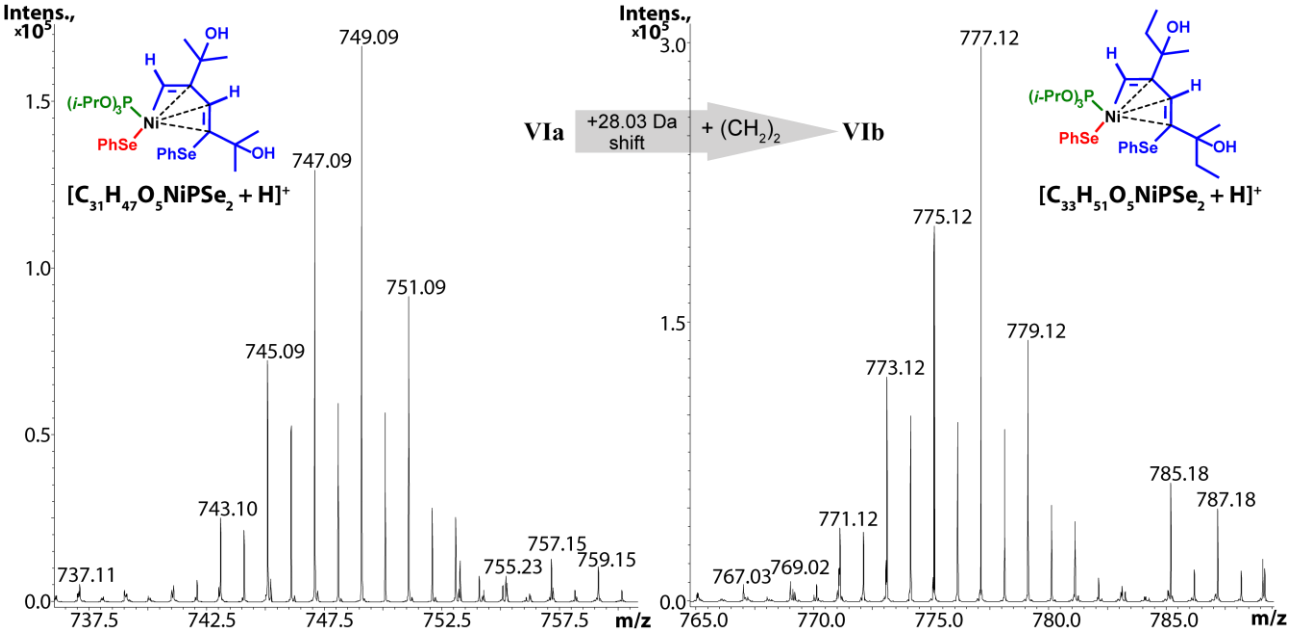
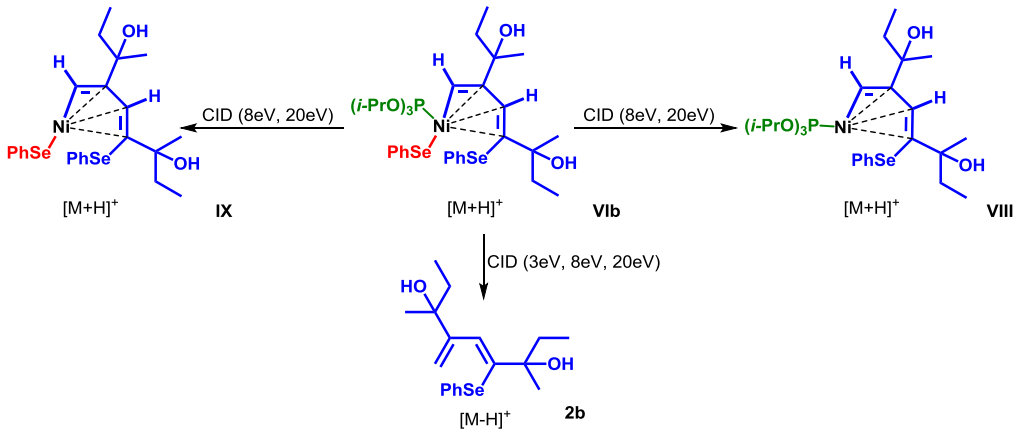


Figure 2. The ESI-(+MS) experiments for the homologous alkynes 2-methylbut-3-yn-2-ol (**1a**) and 3-methylpent-1-yn-3-ol (**1b**). A shift of 28 Da for complex **VI** (see Scheme 4 for structures of **VIa** and **VIb**).

The nickel complex **VIb** was selected for ESI-(+MS/MS) experiments *via* CID at different values of the laboratory-frame collision energy (E_{Lab}) (Scheme 5). When values as low as E_{Lab} = 3 eV were applied to the $[M+H]^+$ ion of **VIb**, the appearance of a signal from diene **2b** was clearly observed in the ESI-(+MS/MS) spectrum. This fact confirmed product formation from **VIb** and indicated weak binding of a mono-selenosubstituted diene fragment to the Ni center. Increasing the E_{Lab} up to 8 eV caused the independent cleavage of Ni–Se and Ni–P bonds in **VIb** and the respective formation of the complexes **VIII** and **IX** (Scheme 5). The corresponding mass spectrum of **VIII**, obtained *via* the CID of **VIb**, was experimentally detected (Figure S2 in the Supporting

Information).

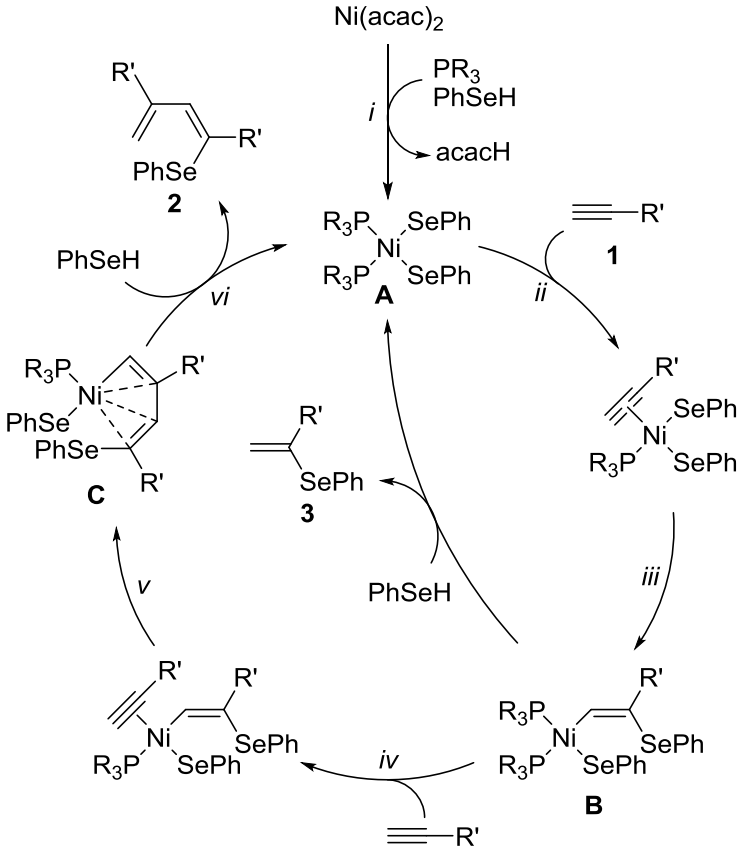


Scheme 5. The fragmentation pathways of complex **VIb** during the ESI-(+MS/MS) experiments with different values of the laboratory-frame collision energy (E_{Lab}).

In summary, based on the ESI-MS and ESI-MS/MS studies, a plausible overall mechanism for the formation of mono-selenosubstituted dienes **2** can be proposed (Scheme 6). At the starting point (*i*), catalytically active nickel complexes (**A**) were formed from the $Ni(acac)_2$ catalyst precursor. Then, the coordination of the alkyne to nickel takes place (*ii*), followed by alkyne insertion into the Ni–Se bond to generate complex **B** (*iii*). Protonolysis of this complex by PhSeH leads to alkene **3**. The competitive process of coordination and insertion of the second alkyne molecule (*iv*, *v*) results in the formation of a diene moiety.[30] Finally, protonolysis of the complex **C** by PhSeH leads to product formation and the regeneration of complex **A** (*vi*). The alternative possibility of C–Se reductive elimination can be excluded because formation of the bis-selenosubstituted diene was not observed in the experiment (Scheme S2 in the Supporting Information). The involvement of protonolysis in the studied system was independently confirmed by a separate experiment in the presence of an acid (Scheme S3 in the Supporting Information). Most likely protonolysis of the complex **IV** is favored over reductive elimination since the reaction results in the formation of mono-selenosubstituted dienes rather than bis-selenosubstituted ones.

Within the proposed mechanism, we can rationalize the formation of only one type of diene framework. The insertion of the alkyne **1** into the Ni–Se bond, followed by the insertion of the alkyne into the Ni–C bond, mediated the formation of a specific 1-PhSe-1,3-diene moiety. In both alkyne insertion steps, the metal center was bound to the least-substituted carbon atom of the alkyne, thus directing the radical (R) out of the metal center. As a result, only one type of diene skeleton was accessible during the catalytic cycle. The preferential *s-gauche* geometry arrangement was maintained in complex **C** due to coordination to the metal center and released in the structure

of product **2**. Within the catalytic cycle we can also rationalize the role of the phosphine ligand: fine tuning is required in order to facilitate coordination and insertion of the second alkyne molecule (steps *iv* and *v*). Another important feature of the catalytic system is to avoid protonolysis at the earlier stage (in complex **B**) and to avoid C–Se reductive elimination in both complexes **B** and **C**.



Scheme 6. The proposed mechanism of the catalytic cycle.

3. Conclusions

We have developed an efficient Ni-based catalytic system that allowed selective synthesis of previously unknown mono-selenosubstituted 1,3-dienes starting from easily available terminal alkynes and PhSeH. The unique properties of the catalytic system made it possible the exclusive formation of one type of the diene. Developed synthetic procedure governed the yields up to 86 % under mild reaction conditions (r.t. – 40^{o}C). The synthetic protocol developed here was tolerant to various alkynes and can easily be scaled-up to prepare gram quantities of Se-functionalyzed dienes.

Using combination of ESI-MS and ESI-MS/MS methods the mechanism of the catalytic reaction was studied and the key Ni-containing species involved in the reaction were successfully detected in the mass-spectra. The proposed catalytic cycle rationalized the exclusive formation of *Z*-

1-PhSe-1,3-dienes *via* a sequence of regioselective alkyne insertions into the Ni–Se and Ni–C bonds.

4. Experimental section

4.1 General.

Unless otherwise noted, the synthetic work was carried out under argon atmosphere. The reagents were obtained from commercial sources and were used as supplied (checked by NMR before use). $Ni(acac)_2$ was dried under vacuum (0.005 - 0.02 Torr, 60°C, 30 min) before use. The solvents were purified according to published methods.

All NMR measurements were performed using a three channel 600 MHz spectrometer operating at 600.1, 242.9, 150.9, 114.5 MHz for the nuclei of ^{1}H, ^{31}P, ^{13}C and ^{77}Se, respectively. The spectra were processed on a Linux workstation using the TopSpin 2.1 software package. All 2D spectra were recorded using an inverse triple resonance probehead with an active shielded Z-gradient coil. ^{1}H and ^{13}C chemical shifts are reported relative to the corresponding solvent signals used as internal reference, whereas external $Ph_2Se_2/CDCl_3$ (δ = 463.0 ppm) was used for ^{77}Se. The yields given below were calculated based on the initial amount of the PhSeH.

The high-resolution mass spectra were recorded on a Q-TOF instrument equipped with an electrospray ionization (ESI) ion source. The measurements were performed in positive (+MS; +MS/MS) ion mode (HV capillary: 4500 V; HV End Plate offset: -500 V) with a scan range m/z of 50 - 3000. External calibration of the mass spectrometer was performed with Electrospray Calibrant Solution (Fluka). Direct syringe injection (a flow rate of 3 μL/min) was used for all analyzed samples (solutions in MeOH). Nitrogen was used as the nebulizer gas (0.4 bar), dry gas (4.0 L/min) and collision gas for all MS/MS experiments; the dry temperature was set at 180 ºC.

4.2 General synthetic procedure for 2a-c, e-j.

$Ni(acac)_2$ (1×10^{-5} mol) and PPh_2Cy (1×10^{-4} mol) were placed in a screw-capped test tube followed by the addition of 0.2 ml of argon-flushed toluene, alkyne (2×10^{-3} mol) and Et_3N (5×10^{-5} mol). A light-green solution was formed within 1-2 min upon stirring at room temperature. The reaction mixture was heated to the appropriate temperature (Table 4), and PhSeH (5×10^{-4} mol) was added dropwise using a syringe pump over the time period indicated in Table 4. After PhSeH was added, the reaction was continued for an additional 5 min and then cooled to room temperature.

After completion of the reaction, the products were purified by column chromatography on silica with hexane/ethylacetate gradient elution. After drying in vacuum, pure products were obtained. In all cases, the structures of the products were confirmed with ^{1}H, $^{13}C\{^{1}H\}$ and $^{77}Se\{^{1}H\}$

NMR. The stereochemistry was determined using 2D NOESY and ^{1}H-^{77}Se HMQC NMR experiments.

4.3 Procedure for scaled synthesis of 2a, i.

$Ni(acac)_2$ (1×10^{-4} mol) and PPh_2Cy (1×10^{-3} mol) were placed in a screw-capped test tube followed by the addition of 2 ml of argon-flushed toluene, alkyne (2×10^{-2} mol) and Et_3N (5×10^{-4} mol). A light-green solution was formed in 1-2 min upon stirring at room temperature. The reaction mixture was heated to the appropriate temperature (Table 4), and PhSeH (5×10^{-3} mol) was added dropwise using a syringe pump over the time period indicated in Table 4. After PhSeH was added, the reaction was continued for an additional 5 min and then cooled to room temperature.

After completion of the reaction, the products were purified by column chromatography on silica with hexane/ethylacetate gradient elution. After drying in vacuum, pure products were obtained. In all cases, the structures of the products were confirmed with ^{1}H, ^{13}C and ^{77}Se NMR. The stereochemistry was determined using 2D NOESY and ^{1}H-^{77}Se HMQC NMR experiments.

4.4 General synthetic procedure for phosphine-free synthesis of 2a, 2d.

$Ni(acac)_2$ (1×10^{-5} mol) was placed in a screw-capped test tube followed by the addition of 0.2 ml of argon-flushed toluene, alkyne (2×10^{-3} mol) and Et_3N (5×10^{-5} mol). A light-green solution was formed in 1-2 min upon stirring at room temperature. The reaction mixture was heated to the appropriate temperature (Table 4), and PhSeH (5×10^{-4} mol) was added dropwise using a syringe pump over the time period indicated in Table 4. After PhSeH was added, the reaction was continued for an additional 5 min and then cooled to room temperature.

After completion of the reaction, the products were purified by column chromatography on silica with hexane/ethylacetate gradient elution. After drying in vacuum, pure products were obtained. The structures of the products were confirmed with ^{1}H, ^{13}C and ^{77}Se NMR.

4.5. Mechanistic ESI-MS study of the catalytic reaction.

$Ni(acac)_2$ (1×10^{-5} mol) and $P(O\textit{i}\text{-}Pr)_3$ (1×10^{-4} mol) were placed in a screw-capped test tube followed by the addition of 0.5 ml of HPLC-grade methanol and corresponding alkyne (2×10^{-3} mol). A light-green solution was formed in 1-2 min upon stirring at room temperature. The reaction mixture was heated to 40°C, and PhSeH (2×10^{-4} mol) was added dropwise over 10 min using a syringe pump. After this time, the tube was centrifuged (5 min., 4,000 rpm). An aliquot (7 μl) of the crude reaction mixture was diluted with MeOH (0.5 ml) and immediately injected into the ion source of the mass spectrometer. An aliquot (30 μl) of the crude reaction mixture was taken

independently for NMR analysis. The systems without alkyne, $Ni(acac)_2/P(i\text{-}PrO)_3/MeOH$ and $PhSeH/Ni(acac)_2/P(i\text{-}PrO)_3/MeOH$, were analyzed in exactly the same manner.

4.6 Compounds characterization.

(Z)-2,6-dimethyl-5-methylene-3-(phenylselanyl)hept-3-ene-2,6-diol (2a) yellow oil, 86 % (0.1364 g), 78 % (1.49 g) for scaled reaction. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.40 (d, *J* = 7.4 Hz, 2H, Ar), 7.22 – 7.13 (m, 3H, Ar), 6.94 (s, 1H, CH=), 5.19 (s, 1H, CH=), 5.18 (s, 1H, CH=), 2.87 (s, 1H, OH), 1.74 (s, 1H, OH), 1.49 (s, 6H, CH_3), 1.23 (s, 6H, CH_3). $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 151.37, 142.95, 133.20, 133.08, 131.12, 129.10, 126.48, 112.90, 75.45, 72.91, 29.88, 29.19. $^{77}Se\{^1H\}$ NMR (114 MHz, $CDCl_3$) δ 287.36. HRMS (ESI-TOF) m/z: $[M - H]^+$ Calcd for $C_{16}H_{21}O_2Se$ 325.0702; Found 325.0709. Anal. calcd for $C_{16}H_{22}O_2Se$: C 59.07; H 6.82; Se 24.27. Found: C 59.44; H 7.18; Se 23.92.

(Z)-3,7-dimethyl-6-methylene-4-(phenylselanyl)non-4-ene-3,7-diol (2b) (mixture of diastereomers), yellow oil, 80 % (0.1418 g). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.42 (d, *J* = 7.4 Hz, 2H, Ar), 7.23 – 7.14 (m, 3H, Ar), 6.81 (s, 1H, CH=), 5.23 (s, 1H, CH=), 5.22 (s, 1H, CH=, second diastereomer), 5.18 (s, 1H, CH=), 2.50 (br. s, 1H, OH), 1.83 – 1.69 (m, 2H, CH_2), 1.61 – 1.49 (m, 3H, CH_2, OH), 1.44 (s, 3H, C-CH_3), 1.20 (s, 3H, C-CH_3), 1.18 (s, 3H, C-CH_3, second diastereomer), 0.88 (t, *J* = 7.5 Hz, 3H, CH_2-**CH_3**), 0.81 (t, *J* = 7.4 Hz, 3H, CH_2-**CH_3**). $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 150.37, 150.32, 141.60, 141.51, 134.80, 134.74, 133.17, 131.23, 131.20, 129.15, 126.56, 114.12, 77.80, 77.75, 75.35, 75.34, 27.27, 27.09, 26.98, 26.94, 8.57, 8.22. $^{77}Se\{^1H\}$ NMR (114 MHz, $CDCl_3$) δ 287.89, 286.88. HRMS (ESI-TOF) m/z: $[M - H]^+$ Calcd for $C_{18}H_{25}O_2Se$ 353.1015; Found 353.1008.

(Z)-6-methylene-4-(phenylselanyl)non-4-ene-2,8-diol (2c) (mixture of diastereomers), brown oil, 58 % (0.0979 g). ^{1}H NMR (600 MHz, $CDCl_3$, first eluted diastereomer) δ 7.54 – 7.48 (m, 2H, Ar), 7.34 – 7.26 (m, 3H, Ar), 6.32 (s, 1H, CH=), 5.28 (s, 1H, CH=), 5.04 (s, 1H, CH=), 3.99 – 3.89 (m, 2H, CH_2), 2.39 (dt, *J* = 13.3 Hz, 3,6 Hz, 1H, C**H**H), 2.30 – 2.17 (m, 3H, CH_2, C**H**H), 2.10 (br. s, 2H, 2OH), 1.24 (d, *J* = 6.1 Hz, 3H, CH_3), 1.05 (d, *J* = 6.4 Hz, 3H, CH_3).

^{1}H NMR (600 MHz, $CDCl_3$, second eluted diastereomer) δ 7.54 – 7.48 (m, 2H, Ar), 7.34 – 7.26 (m, 3H, Ar), 6.31 (s, 1H, CH=), 5.29 (s, 1H, CH=), 5.04 (s, 1H, CH=), 3.99 – 3.89 (m, 2H, CH_2), 2.39 (dt, *J* = 13.3 Hz, 3,6 Hz, 1H, C**H**H), 2.30 – 2.17 (m, 3H, CH_2, C**H**H), 2.10 (br. s, 2H, 2OH), 1.24 (d, *J* = 6.1 Hz, 3H, CH_3), 1.03 (d, *J* = 6.3 Hz, 3H, CH_3).

$^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$, first eluted diastereomer) δ 142.99, 135.15, 133.93, 133.84,

129.35, 128.28, 119.27, 66.66, 66.51, 47.66, 46.89, 22.75, 22.41.

$^{13}C\{^{1}H\}$ NMR (126 MHz, $CDCl_3$, second eluted diastereomer) δ 143.14, 135.25, 133.93, 133.34, 129.35, 128.33, 119.46, 66.41, 66.21, 47.62, 47.07, 22.75, 22.48.

$^{77}Se\{^{1}H\}$ NMR (114 MHz, $CDCl_3$, first eluted diastereomer) δ 381.65.

$^{77}Se\{^{1}H\}$ NMR (114 MHz, $CDCl_3$, second eluted diastereomer) δ 377.47.

HRMS (ESI-TOF) m/z: $[M - H]^+$ Calcd for $C_{16}H_{21}O_2Se$ 325.0702; Found 325.0706.

(Z)-5-methylene-3-(phenylselanyl)hept-3-ene-2,6-diol (2d), **(mixture of diastereomers)**, yellow oil, 51 % (0.0821 g). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.50 – 7.45 (m, 2H, Ar), 7.28 – 7.22 (m, 3H, Ar), 6.82 (s, 1H, CH=), 5.34 (s, 1H, CH=), 5.09 (s, 1H, CH=), 5.06 (s, 1H, CH=, second diastereomer),4.44 – 4.36 (m, 1H, CH), 4.29 – 4.21 (m, 1H, CH), 2.09 (br. s, 2H, OH), 1.36 (d, *J* = 6.3 Hz, 3H, CH_3), 1.32 (d, *J* = 6.5 Hz, 3H, CH_3, second diastereomer), 1.30 (d, *J* = 6.5 Hz, 3H, CH_3). $^{13}C\{^{1}H\}$ NMR (151 MHz, $CDCl_3$) δ 148.54, 148.52, 141.30, 140.93, 133.33, 133.21, 129.37, 129.19, 128.31, 127.58, 127.54, 115.05, 115.03, 71.34, 71.26, 71.10, 70.96, 23.40, 23.27, 22.33, 22.18. $^{77}Se\{^{1}H\}$ NMR (114 MHz, $CDCl_3$) δ 332.03, 328.35. HRMS (ESI-TOF) m/z: $[M - H]^+$ Calcd for $C_{14}H_{17}O_2Se$ 297.0389; Found 297.0394.

(Z)-7-methylene-5-(phenylselanyl)undec-5-ene-1,11-diol (2e), brown oil, 46 % (0.0925 g). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.52 – 7.49 (m, 2H , Ar), 7.30 – 7.23 (m, 3H, Ar), 6.24 (s, 1H, CH=), 5.13 (s, 1H, CH=), 4.91 (s, 1H, CH=), 3.65 (t, *J* = 6.3 Hz, 2H, CH_2), 3.51 (t, *J* = 6.5 Hz, 2H, CH_2), 2.22 (t, *J* = 7.3 Hz, 2H, CH_2), 2.18 (t, *J* = 7.3 Hz, 2H, CH_2), 1.65 – 1.46 (m, 10H, $4CH_2$, 2OH). $^{13}C\{^{1}H\}$ NMR (151 MHz, $CDCl_3$) δ 145.72, 135.72, 134.63, 134.08, 131.80, 128.95, 127.61, 115.44, 62.76, 62.60, 38.21, 36.59, 32.31, 31.71, 25.39, 24.39. ^{77} $Se\{^{1}H\}$ NMR (114 MHz, $CDCl_3$) δ 375.43. HRMS (ESI-TOF) m/z: $[M - H]^+$ Calcd for $C_{18}H_{25}O_2Se$ 353.1002; Found 353.1015.

(Z)-5-methylene-3-(phenylselanyl)hept-3-ene-1,7-diol (2f), yellow oil, 42 % (0.1320 g). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.50 (d, *J* = 7.1 Hz, 2H, Ar), 7.32 – 7.26 (m, 3H, Ar), 6.34 (s, 1H, CH=), 5.27 (s, 1H, CH=), 5.05 (s, 1H, CH=), 3.73 (t, *J* = 6.1 Hz, 2H, CH_2), 3.64 (t, *J* = 6.2 Hz, 2H, CH_2), 2.45 (t, *J* = 6.0 Hz, 2H, CH_2), 2.40 (t, *J* = 6.1 Hz, 2H, CH_2), 2.00 (br. s, 2H, 2OH). $^{13}C\{^{1}H\}$ NMR (151 MHz, $CDCl_3$) δ 142.79, 136.56, 134.87, 133.68, 132.51, 129.36, 128.16, 118.94, 61.34, 61.09, 41.32, 40.10. $^{77}Se\{^{1}H\}$ NMR (114 MHz, $CDCl_3$) δ 370.99. HRMS (ESI-TOF) m/z: $[M - H]^+$ Calcd for $C_{14}H_{17}O_2Se$ 297.0389; Found 297.0392.

(Z)-(8-methylenetridec-6-en-6-yl)(phenyl)selane (2g), yellow oil, 50 % (0.0888 g).

^{1}H NMR (600 MHz, $CDCl_3$) δ 7.53 – 7.48 (m, 2H, Ar), 7.28 – 7.19 (m, 3H, Ar), 6.23 (s, 1H, CH=), 5.11 (s, 1H,CH=), 4.88 (s, 1H, CH=), 2.21-2.11 (m, 4H, CH_2), 1.52 – 1.40 (m, 4H, $2CH_2$), 1.35 – 1.29 (m, 4H, $2CH_2$), 1.21 – 1.16 (m, 2H, CH_2), 1.15 – 1.08 (m, 2H, CH_2), 0.90 (t, *J* = 6.9 Hz, 3H, CH_3), 0.82 (t, *J* = 7.3 Hz, 3H, CH_3). ^{13}C{^{1}H} NMR (151 MHz, $CDCl_3$) δ 146.52, 136.12, 134.78, 131.90, 131.50, 128.99, 127.56, 114.94, 38.79, 37.12, 31.67, 31.11, 29.23, 28.16, 22.73, 22.51, 14.22, 14.12. ^{77}Se{^{1}H} NMR (114 MHz, $CDCl_3$) δ 375.94. HRMS (ESI-TOF) m/z: $[M - H]^+$ Calcd for $C_{20}H_{29}Se$ 349.1430; Found 349.1437.

(Z)-(7-methyleneundec-5-en-5-yl)(phenyl)selane (2h),yellow oil, 49 % (0.1599 g), 62 % (0.94 g) for scaled reaction. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.52 – 7.49 (m, 2H, Ar), 7.28 – 7.22 (m, 3H, Ar), 6.23 (s, 1H, CH=), 5.11 (s, 1H, CH=), 4.88 (s, 1H, CH=), 2.18 (t, *J* = 7.5 Hz, 2H, CH_2), 2.14 (t, *J* = 7.5 Hz, 2H, CH_2), 1.54 – 1.28 (m, 6H, CH_2), 1.20 – 1.13 (m, 2H, CH_2), 0.93 (t, *J* = 7.2 Hz, 3H, CH_3), 0.78 (t, *J* = 7.4 Hz, 3H, CH_3). ^{13}C{^{1}H} NMR (151 MHz, $CDCl_3$) δ 146.38, 136.04, 134.74, 131.83, 131.42, 128.93, 127.52, 114.90, 38.40, 36.77, 31.66, 30.57, 22.45, 21.91, 14.07, 13.88. ^{77}Se{^{1}H} NMR (114 MHz, $CDCl_3$) δ 377.69. HRMS (ESI-TOF) m/z: $[M - H]^+$ Calcd for $C_{18}H_{25}Se$ 321.1117; Found 321.1120. Anal. calcd for $C_{18}H_{26}Se$: C 67.27; H 8.16; Se 24.57. Found: C 67.50; H 8.32; Se 24.18.

(Z)-(6-methylenenon-4-en-4-yl)(phenyl)selane (2i), yellow oil, 44 % (0.0635g). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.52 – 7.49 (m, 2H, Ar), 7.29 – 7.22 (m, 3H, Ar), 6.23 (s, 1H, CH=), 5.12 (s, 1H, CH=), 4.89 (s, 1H, CH=), 2.16 (t, *J* = 7.5 Hz, 2H, CH_2), 2.12 (t, *J* = 7.3 Hz, 2H, CH_2), 1.55 – 1.40 (m, 4H, $2CH_2$), 0.94 (t, *J* = 7.3 Hz, 3H, CH_3), 0.77 (t, *J* = 7.5 Hz, 3H, CH_3). ^{13}C{^{1}H} NMR (151 MHz, $CDCl_3$) δ 146.22, 135.77, 134.74, 132.06, 131.48, 129.00, 127.57, 115.16, 40.72, 39.22, 22.60, 21.61, 13.95, 13.33. ^{77}Se{^{1}H} NMR (114 MHz, $CDCl_3$) δ 375.01. HRMS (ESI-TOF) m/z: $[M - H]^+$ Calcd for $C_{16}H21Se$ 293.0803; Found 293.0797.

(Z)-(2,8-dimethyl-6-methylenenon-4-en-4-yl)(phenyl)selane (2j), yellow oil, 52 % (0.0931 g). ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.52 – 7.49 (m, 2H, Ar), 7.27 – 7.22 (m, 3H, Ar), 6.16 (s, 1H, CH=), 5.11 (s, 1H, CH=), 4.90 (s, 1H, CH=), 2.07 (d, *J* = 7.2 Hz, 2H, CH_2), 1.97 (d, *J* = 6.9 Hz, 2H, CH_2), 1.90 – 1.82 (m, 1H, CH), 1.81 – 1.73 (m, 1H, CH), 0.93 (d, *J* = 6.6 Hz, 6H, CH_3), 0.75 (d, *J* = 6.6 Hz, 6H, CH_3). ^{13}C{^{1}H} NMR (151 MHz, $CDCl_3$) δ 145.35, 135.70, 135.01, 132.81, 132.35, 128.96, 127.65, 116.32, 47.83, 46.95, 27.52, 27.38, 22.67, 22.05. ^{77}Se{^{1}H} NMR (114 MHz, $CDCl_3$) δ 377.90. HRMS (ESI-TOF) m/z: $[M - H]^+$ Calcd for $C_{18}H_{25}Se$ 321.1117; Found 321.1109.

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Supporting Information.

^{1}H, ^{13}C{^{1}H} and ^{77}Se{^{1}H} NMR spectra of new compounds **2a**-**2i**, X-Ray structure determination of compound **2a**, mechanistic schemes, figures of 2D NOESY NMR, and ESI-MS/MS spectra are included. This material is available free of charge via the Internet at http://pubs.acs.org.

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[27] P(*i*-PrO)$_3$ ligand was superior in terms of ionization under ESI conditions as compared to the other studied PR_3 ligands. Ni complexes with P(*i*-PrO)$_3$ ligand were easily detected by ESI-MS.

[28] The fact of detection of the Ni(acac)$_2$ in the presence of excess of PhSeH looks somewhat

unusual, since substitution of acac ligand with the PhSe group is known to proceed fast (see ref. 15). We checked this three component mixture with ^{1}H NMR and release of acacH was proven to be fast and complete at room temperature. We suggest that formation of $Ni(acac)_2$ takes place directly upon electrospraying in the charged droplets. For experimental proof we performed the independent control ESI-MS analysis of $Ni(CH_3COO)_2$/acacH (1/2.5 molar ratio) mixture dissolved in methanol. Indeed, the signals of $Ni(acac)_2$ (both protonated and sodium adduct) together with the $[Ni_2(acac)_3]^+$ cation were detected as the most abundant iones.

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[30] Indeed, two pathways of insertion of the second alkyne molecule are possible, into either the Ni–C or Ni–Se bond (Scheme S1 in Supporting Information). Based on the experimental results, we can rule out the latter case, because a bis-selenosubsituted diene would be formed after reductive elimination (not observed in the experiment). Therefore, the catalytic cycle involves the insertion of the second alkyne molecule into the Ni–C bond and the formation of a diene skeleton in the coordination sphere of the metal (Scheme 6).