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Tetrahedron 64 (2008) 392–398
Tetrahedron
www.elsevier.com/locate/tet

Modular chiral β-selenium-, sulfur-, and tellurium amides: synthesis and application in the palladium-catalyzed asymmetric allylic alkylation

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Received 20 July 2007; received in revised form 13 October 2007; accepted 23 October 2007
Available online 25 October 2007

Abstract

A series of modular chiral β-chalcogen amides have been efficiently synthesized from inexpensive and easily available 2-oxazolines. All the selenium, sulfur, and tellurium compounds were evaluated as chiral ligands in the palladium-catalyzed asymmetric allylic alkylation. The corresponding alkylated products were obtained in excellent enantiomeric excess, using BSA/CH_2Cl_2 as the base/solvent system.

Keywords: Selenium; Sulfur; Tellurium; Chiral catalyst; Palladium; Asymmetric allylic alkylation

1. Introduction

The search for new and properly designed chiral ligands in asymmetric catalysis is currently one of the major challenges in synthetic organic chemistry.[1] Thus, a practical, modular, and concise strategy should be applied to facilitate the preparation of a wide range of enantiopure ligands from easily available starting materials.

Chiral nitrogen compounds bearing an organochalcogen moiety and their metal complexes have been frequently employed as effective catalysts in various enantioselective transformations.[2] For instance, selenium- and sulfur-containing chiral ligands have been reported as efficient catalysts in several different enantioselective reactions, such as the enantioselective diethylzinc[3] and alkynylzinc[4] addition to aldehydes, and conjugate addition to enones.[5]

Among the transition metal-catalyzed reactions, the palladium-catalyzed allylic alkylation is a versatile, widely used process in organic synthesis for the enantioselective formation of carbon–carbon and carbon–heteroatom bonds.[6] Moreover, it is an interesting process in the synthesis of optically active small molecules and in the total synthesis of natural products.[7] Many chiral organochalcogenides have also demonstrated their utility in this process.[8]

Following our interest in the preparation and application of chiral organochalcogen compounds in asymmetric transformations, we report in this full account the behavior of a modular series of selenium-, sulfur-, and tellurium-chalcogen amides starting from chiral 2-oxazolines, as depicted in the retrosynthetic analysis (Fig. 1). All the β-organochalcogen amides had their efficiency examined as chiral ligands in the enantioselective palladium-catalyzed asymmetric allylic alkylation reaction.

2. Results and discussion

The modular chiral β-chalcogen amides were rapidly synthesized starting from 2-oxazolines as inexpensive and easily

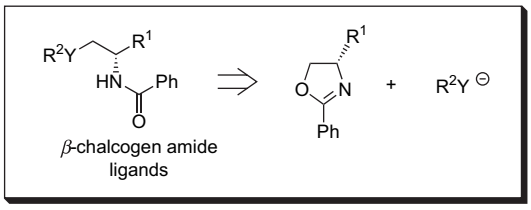

Figure 1. Retrosynthetic analysis of the chiral β-chalcogen amides.

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doi:10.1016/j.tet.2007.10.086

accessible chiral pool starting materials. According to our previous communication,[9] the respective reaction proceeds through the formation of an oxazolinium intermediate,[10] and the regio- and chemoselective nucleophilic attack of the chalcogenide at the C(5) position of the chiral 2-oxazoline leads to the C(5)–O(1) bond cleavage, furnishing the corresponding chiral β-chalcogen amide without any racemization, as determined by chiral HPLC.[11] Thus, the most efficient ring-opening process was achieved when the chalcogenide was generated in situ in the presence of $NaBH_4$ as reducting agent, THF/EtOH (3:1) as the solvent and 1 equiv of freshly distilled TMSCl as a Lewis acid. The first study of the scope and limitations of the ring-opening reaction was conducted in the presence of selenium nucleophiles using the chiral 2-phenyl oxazoline **1a** (R^1=*i*-Pr) as model starting material (Table 1).

As shown in Table 1, the chiral organoselenium compounds **2a–h** were synthesized in good to excellent yields (Table 1, entries 1–8), except for dibutyl diselenide, which furnished the corresponding product **2d** in lower yield (Table 1, entry 4). The ring-opening reaction permits a series of different R^1 groups attached to the oxazoline ring, as the respective products were obtained in up to 93% yield (Table 1, entries 1–3). The present method also tolerates organodiselenides bearing hindered substituents (R^2=2,4,6-Me_3Ph) as well as electron-withdrawing (R^2=*p*-ClPh) and electron-donating groups (R^2=*p*-MeOPh), furnishing the corresponding chiral organoselenides in excellent yields (Table 1, entries 6–8). Moreover, different chiral β-seleno amides containing sulfides, alcohols, ethers, and ester moieties were prepared in excellent yields according to this convenient method (Table 1, entries 9–13).

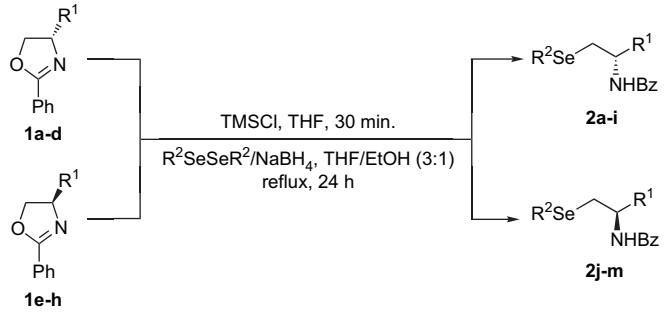
Based on the successful approach developed in the preparation of a wide range of chiral β-selenium amides by ring-opening reaction we decided to extend our studies in order to prepare a series of chiral organochalcogenide compounds using sulfur and tellurium nucleophilic species. Thus, different β-thio and β-tellurium amides were obtained in a similar way, as depicted in Table 2.

The corresponding chiral β-thio amides **3a–e** were obtained with yields ranging from 68 to 83% (Table 2, entries 1–5). As observed with selenium nucleophiles, the ring-opening reaction also tolerates the presence of different R^1 groups at the oxazoline ring (Table 2, entries 1–3) as well as substituents attached at the aromatic ring of the organosulfur moiety (Table 2, entries 4 and 5). The present reaction was also evaluated in the presence of a phenyltellurolate, furnishing the desired chiral β-telluro amide **4** in 52% yield (Table 2, entry 6).

With the chiral compounds **2**, **3**, and **4** in hand, we turned our attention to an investigation of their potential as ligands in the palladium-catalyzed asymmetric allylic alkylation. We then decided to evaluate the behavior of the catalysts under conditions previously developed by us[9] for the chiral β-seleno amide **2a**. Thus, the catalytic asymmetric reaction, using standard substrates, was performed using the chiral β-chalcogen amide (5 mol %) and $[Pd(\eta^3\text{-}C_3H_5)Cl]_2$ (2.5 mol %) in the presence of CH_2Cl_2 and BSA/KOAc as a solvent/base system, as summarized in Table 3.

We observe that the ligands **2a–h** afforded the alkylated product (*R*)-**7a** in similar chemical yield and in up to 98% ee (Table 3, entries 1–8). The catalytic process tolerates different alkyl (R^2=Bu and Bn) and aryl groups (R^2=2,4,6-Me_3Ph, *p*-ClPh, and *p*-MeOPh) attached at the selenium atom, showing that variations in the steric and electronic properties do not reduce the ability of the selenium coordinate to the palladium atom. However, ligands **2i–m** bearing different functional groups had a negative effect in the asymmetric reaction, furnishing the respective racemic alkylated products in very low yields (Table 3, entries 9–13).

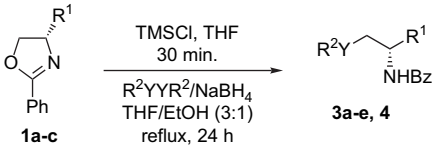
Table 1
Preparation of chiral β-seleno amides by ring-opening reaction of 2-oxazolines



Entry	Oxazoline	R^1	R^2	**2**, Yield[a,b] (%)
1	**1a**	*i*-Pr	Ph	**2a**, 93
2	**1b**	*i*-Bu	Ph	**2b**, 82
3	**1c**	Bn	Ph	**2c**, 84
4	**1a**	*i*-Pr	Bu	**2d**, 27
5	**1a**	*i*-Pr	Bn	**2e**, 71
6	**1a**	*i*-Pr	2,4,6-Me_3Ph	**2f**, 79
7	**1a**	*i*-Pr	*p*-ClPh	**2g**, 82
8	**1a**	*i*-Pr	*p*-MeOPh	**2h**, 84
9	**1d**	$(CH_2)_2SMe$	Ph	**2i**, 72
10	**1e**	CH_2OH	Ph	**2j**, 90
11	**1f**	CH_2OBn	Ph	**2k**, 78
12	**1g**	CH_2OEt	Ph	**2l**, 87
13	**1h**	CO_2Me	Ph	**2m**, 51

[a] Isolated yield of the corresponding product.
[b] TMSCl was freshly distilled.

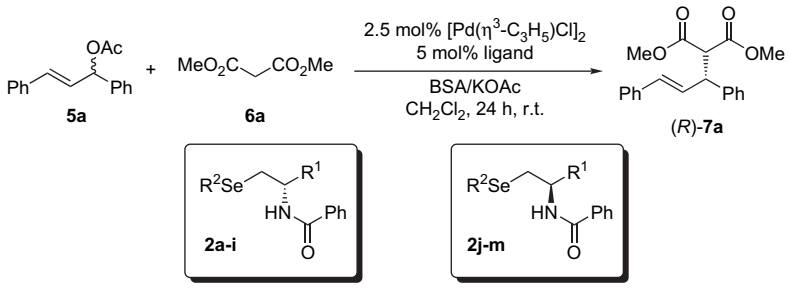
Table 2
Preparation of chiral β-thio and β-telluro amides by ring-opening reaction of 2-oxazolines



Entry	Oxazoline	R^1	R^2	Y	Product, yield[a,b] (%)
1	**1a**	*i*-Pr	Ph	S	**3a**, 83
2	**1b**	*i*-Bu	Ph	S	**3b**, 74
3	**1c**	Bn	Ph	S	**3c**, 70
4	**1a**	*i*-Pr	*o*-ClPh	S	**3d**, 68
5	**1a**	*i*-Pr	*p*-MeOPh	S	**3e**, 76
6	**1a**	*i*-Pr	Ph	Te	**4**, 52

[a] Isolated yield of the corresponding product.
[b] TMSCl was freshly distilled.

Table 3
Palladium-catalyzed asymmetric allylic alkylation with **2j–m**



Entry	Ligand	R^1	R^2	Yield[a] (%)	ee[b] (%)
1	**2a**	*i*-Pr	Ph	97	98
2	**2b**	*i*-Bu	Ph	95	89
3	**2c**	Bn	Ph	90	88
4	**2d**	*i*-Pr	Bu	96	97
5	**2e**	*i*-Pr	Bn	94	96
6	**2f**	*i*-Pr	2,4,6-Me_3Ph	89	91
7	**2g**	*i*-Pr	*p*-ClPh	96	95
8	**2h**	*i*-Pr	*p*-MeOPh	96	96
9	**2i**	$(CH_2)_2$SMe	Ph	12	—
10	**2j**	CH_2OH	Ph	15	—
11	**2k**	CH_2OBn	Ph	13	—
12	**2l**	CH_2OEt	Ph	12	—
13	**2m**	CO_2Me	Ph	08	—

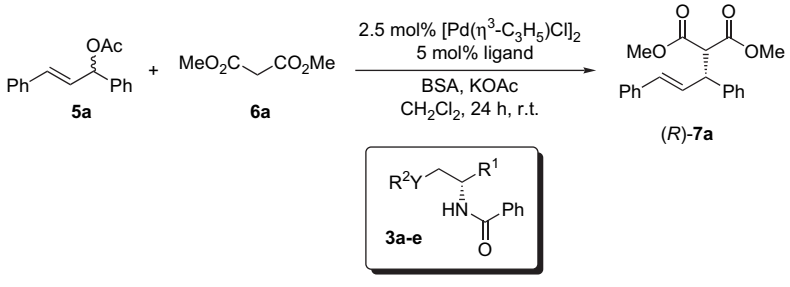
[a] Isolated yields.
[b] Determined by HPLC with a Daicel Chiralcel OD column, hexane/isopropanol 99:1; 0.5 mL/min; 254 nm.

The chiral organosulfur catalysts **3a–e** and the organotellurium **4** compounds were also evaluated in the present catalytic reaction under the same reaction conditions, as depicted in Table 4. This study allowed us to make a direct comparison of the ability of selenium, sulfur, and tellurium to complex with palladium and to catalyze the asymmetric alkylation reaction.

The sulfur-derived catalysts **3a–e** delivered the alkylated products in good to excellent yields and in up to 86% ee (Table 4, entry 1) . As noted with the respective selenium-containing analogues, the asymmetric reaction in the presence of the chiral sulfur catalysts also tolerates diverse alkyl groups (R^1= *i*-Pr, *i*-Bu, Bn) as well as aryl groups (R^2=*o*-ClPh, *p*-MeOPh) attached to the sulfur moiety.

The chiral β-tellurium amide **4** was also evaluated in our catalytic system under the optimal conditions. Thus, the desired product was obtained in 39% yield and 59% ee (Table 4, entry 6). Despite the moderate yield obtained for the

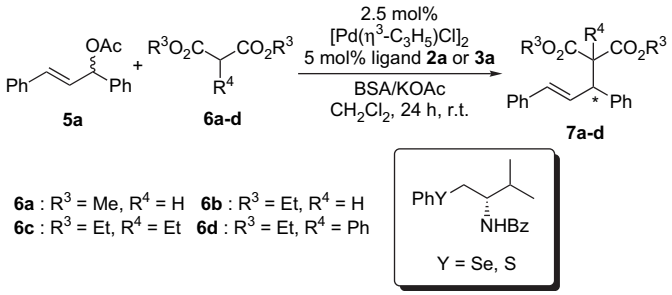
Table 4
Palladium-catalyzed asymmetric allylic alkylation with **3a–e** and **4**



Entry	Ligand	R^1	R^2	Y	Yield[a] (%)	ee[b] (%)
1	**3a**	*i*-Pr	Ph	S	94	86
2	**3b**	*i*-Bu	Ph	S	79	83
3	**3c**	Bn	Ph	S	77	72
4	**3d**	*i*-Pr	*o*-ClPh	S	79	74
5	**3e**	*i*-Pr	*p*-MeOPh	S	84	80
6	**4**	*i*-Pr	Ph	Te	39	59

[a] Isolated yields.
[b] Determined by HPLC with a Daicel Chiralcel OD column, hexane/isopropanol 99:1; 0.5 mL/min; 254 nm.

Table 5
Palladium-catalyzed asymmetric allylic alkylation with **2a** and **3a**



Entry	Y	Malonate	Yield[a] (%)	ee[b,c] (%)
1	Se	**6a**	97	98
2	S	**6a**	94	86
3	Se	**6b**	95	93
4	S	**6b**	89	84
5	Se	**6c**	83	69
6	S	**6c**	61	48
7	Se	**6d**	89	82
8	S	**6d**	68	66

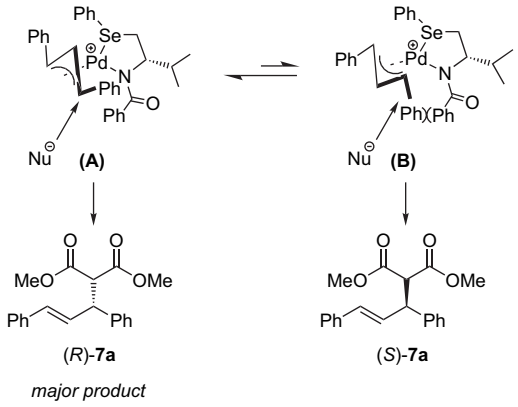
[a] Isolated yields.
[b] Determined by chiral HPLC analysis.
[c] For entries 1–4, the product has an *R* configuration. For entries 5–8, the absolute configuration of the product was not determined.

alkylated product, to the best of our knowledge, this is the first time that an organic telluride has been used as ligand for this kind of transformation.

In addition, we have chosen the most efficient selenium- and sulfur-containing chiral catalysts **2a** and **3a** (R^1=*i*-Pr and R^2=Ph) in the palladium-catalyzed asymmetric allylic alkylation to evaluate them in the presence of substituted malonates, as shown in Table 5. Thus, we could observe that the ligands furnished the respective alkylated products with different enantioselectivities, and in good to excellent yields. For instance, when diethylmalonate **6b** was employed as a nucleophile in the asymmetric reaction, comparable results were obtained to the reactions using dimethylmalonate under the same conditions (Table 5, compare entries 1–2 and entries 3–4). However, when substituted malonates **6c** (R^4=Et) and **6d** (R^4=Ph) were employed in the catalytic reaction, the desired products were obtained in lower yields and in up to 82% ee (Table 5, entry 7), demonstrating that the presence of different groups in the R^4 position shows a negative effect in the formation of a new carbon–carbon bond with a high level of enantioselectivity.

We also note that in all cases presented herein the chiral β-selenium amides have proven to be more efficient than the respective chiral sulfur- and tellurium-containing analogues. This observation of a difference in the behavior among the chalcogenide donors provides evidence for the higher ability of selenium to complex with palladium, leading to a superior level of enantioselection.

In order to propose a plausible explanation of the stereoselectivity observed, a schematic reaction pathway between the dimethylmalonate and the allylic acetate in the presence of the chiral ligand **2a** is shown in Scheme 1.



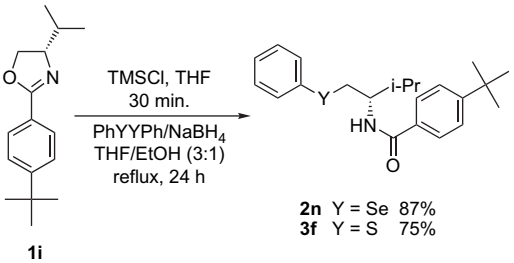
Scheme 1. Plausible reaction pathways for the palladium-catalyzed asymmetric allylic alkylation.

Attack of the nucleophile on the π-allylpalladium complex is believed to take place trans to the better π-acceptor. Thus, we propose that the attack of the nucleophile occurs trans to a selenium donor in a nitrogen–selenium chelate complex, i.e., the nucleophile attacks preferentially at the allylic position trans to the Pd–Se bond in the π-allylpalladium complex.

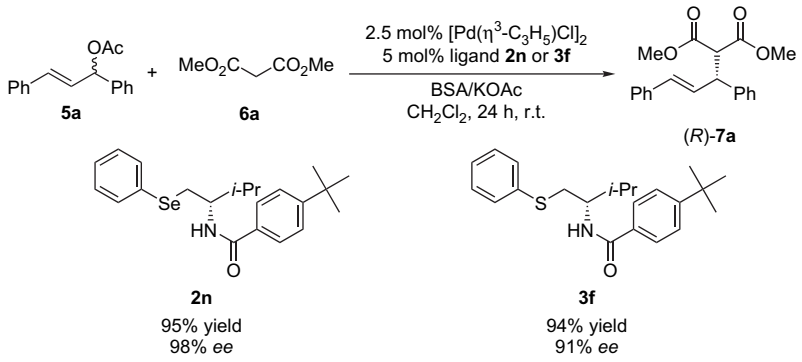
Because the major product obtained is (*R*)-**7**, the reaction appears to proceed preferentially via the intermediate (**A**) in the equilibrium depicted in Scheme 1. Intermediate (**A**), where the allyl group is disposed in a 'W' orientation, seems to be more stable than intermediate (**B**), where the allyl moiety is arranged in a 'M' conformation. We believed that the major interaction that accounts for the difference in the stability of both intermediates would be the steric repulsion between the phenyl terminus of the allylic substrate and the phenyl group attached to the amide, in intermediate (**B**). This unfavorable interaction would explain the predominance of intermediate (**A**) in the equilibrium and the stereoselectivity observed in favor of (*R*)-**7** (Scheme 1).

Taking into consideration the probable influence of the group attached at the amide group in the formation of the intermediates (**A**) and (**B**), we decided to make a structural modification on the general framework of the catalysts and insert a bulkier group than a phenyl ring in the amide position. Thus, we prepared the corresponding chiral organochalcogenide amides **2n** and **3f** by ring-opening reaction of the oxazoline **1i** with phenylselenolate and phenylthiolate in 87 and 75% yields, respectively (Scheme 2).

The chiral organochalcogenide amides **2n** and **3f** bearing a bulkier group at the amide moiety (4-*t*-BuPh) were evaluated



Scheme 2. Preparation of chiral ligands **2n** and **3f**.



Scheme 3. Palladium-catalyzed asymmetric allylic alkylation with **2n** and **3f**.

as ligands in the palladium-catalyzed asymmetric allylic alkylation under same reaction conditions (Scheme 3).

As observed in Scheme 3, the chiral selenium-containing ligand **2n**, equipped with a 4-*t*-BuPh group attached to the amide functional group, furnished similar results when compared with the ligand bearing a phenyl group at the amide moiety **2a**, affording the corresponding alkylated product (*R*)-**7a** with the same level of enantioselectivity (98%) and in comparable chemical yield. However, the chiral sulfur-containing analogue ligand **3f** proved to be more efficient than **3a**, delivering the desired product (*R*)-**7a** with a slight improvement in the enantiomeric excess (91%). Thus, this experimental result supports the proposed reaction pathway (Scheme 1) through the more stable intermediate (**A**), which leads to the major product with the (*R*) configuration.

3. Conclusions

In summary, we have described an extensive study concerning the preparation of chiral β-selenium-, sulfur-, and tellurium amides in a short, high yielding synthetic route and with a modular approach by ring-opening reaction of 2-oxazolines. Furthermore, all the compounds were evaluated as chiral ligands for the palladium-catalyzed asymmetric allylic alkylation of racemic 1,3-diphenyl-2-propenyl acetate with malonates. The corresponding alkylated products were achieved in good to excellent yields and in up to 98% ee. The best results were obtained with the chiral β-selenium amide **2a**, compared to the other organochalcogenide ligands. More interestingly, for the first time an organic telluride has been used for this kind of transformation. This result demonstrates the higher ability of selenium to complex with palladium compared to other chalcogens and thus is an interesting feature for the design of new ligands containing the chalcogen atom.

4. Experimental

4.1. General procedures

All compounds were isolated after column chromatography and showed purity >95% by NMR analysis. Melting points are uncorrected. ^{1}H and ^{13}C NMR spectra were recorded at 400 and 100 MHz, respectively, with tetramethylsilane as internal standard. High resolution mass spectra were recorded on a Brucker BioApex 70e FT-ICR (Bruker Daltonics, Billerica, USA) instrument in ESI-mode. Column chromatography was performed using Merck Silica Gel (230–400 mesh) following the methods described by Still.[12] Thin layer chromatography (TLC) was performed using Merck Silica Gel GF_{254}, 0.25 mm thickness. For visualization, TLC plates were either placed under ultraviolet light or stained with iodine vapor or acidic vanillin. THF was dried over sodium benzophenone ketyl and distilled prior to use. Dichloromethane and acetonitrile were distilled from phosphorus pentoxide. All other solvents were used as purchased unless otherwise noted. Oxazolines were prepared according to the procedures described in the literature.[13] Racemic 1,3-diphenyl-3-acetoxy-prop-1-ene was prepared according to literature procedure.[14] Compounds **2a–m** were prepared according to the procedure described in the literature.[9]

4.2. General procedure for the synthesis of chiral β-chalcogen amides

Under an argon atmosphere, freshly distilled TMSCl (1 mmol) was added to a solution of the appropriate oxazoline (1 mmol) in dry THF (4 mL). The mixture was allowed to stir for at least 30 min. The chalcogenide anion was generated by reaction of the corresponding diorgano dichalcogenide (0.6 mmol) with $NaBH_4$ (1.5 mmol) in a mixture of THF (1.5 mL) and EtOH (0.5 mL) and transferred to the flask containing the oxazolium intermediate. The resulting solution was stirred for 24 h under reflux. The mixture was quenched with a saturated NH_4Cl solution, extracted with CH_2Cl_2 and the combined organic fractions were collected, dried over $MgSO_4$, and filtered. The solvent was removed in vacuo yielding the crude products, which were purified by flash chromatography.

*4.2.1. (S)-4-tert-Butyl-N-(3-methyl-1-(phenylselanyl)butan-2-yl)benzamide **2n***

Yield 87%; white solid; mp 126–128 °C; $[\alpha]_D^{20}$ +68 (*c* 1.0, CH_2Cl_2); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.57–7.50 (m, 4H), 7.40–7.38 (m, 2H), 7.20–7.18 (m, 3H), 6.14 (d, J=8.8 Hz, 1H), 4.23–4.21 (m, 1H), 3.26–3.21 (m, 2H), 2.02–2.00 (m, 2H), 1.32 (s, 9H), 0.97–0.95 (m, 6H); ^{13}C NMR ($CDCl_3$,

100 MHz) δ 166.9, 154.7, 132.8, 131.7, 130.0, 129.1, 127.0, 126.6, 125.3, 54.5, 34.8, 31.9, 31.7, 31.1, 19.4, 18.5; HRMS-ESI *m/z* calcd for $C_{22}H_{29}NOSe+Na^+$ 426.1306, found 426.1301.

4.2.2. (*S*)-*N*-(3-Methyl-1-(phenylthio)butan-2-yl)benzamide **3a**

Yield 83%; white solid; mp 114–116 °C; $[\alpha]_D^{20}$ +45 (*c* 1.0, CH_2Cl_2); ^1H NMR ($CDCl_3$, 400 MHz) δ 7.63 (d, *J*=7.2 Hz, 2H), 7.45–7.34 (m, 5H), 7.23 (t, *J*=7.6 Hz, 2H), 7.15–7.14 (m, 1H), 6.22 (d, *J*=8.4 Hz, 1H), 4.23–4.19 (m, 1H), 3.23–3.21 (m, 2H), 2.10–2.05 (m, 2H), 0.98 (d, *J*=3.6 Hz, 3H), 0.97 (d, *J*=3.6 Hz, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 167.2, 136.1, 134.6, 131.2, 129.7, 129.0, 128.4, 126.8, 126.3, 54.4, 36.9, 30.7, 19.3, 18.4; HRMS-ESI *m/z* calcd for $C_{18}H_{21}NOS+Na^+$ 322.1247, found 322.1248.

4.2.3. (*S*)-*N*-(4-Methyl-1-(phenylthio)pentan-2-yl)-benzamide **3b**

Yield 74%; white solid; mp 108–110 °C; $[\alpha]_D^{20}$ +25 (*c* 1.0, CH_2Cl_2); ^1H NMR ($CDCl_3$, 400 MHz) δ 7.60 (d, *J*=7.2 Hz, 2H), 7.45–7.33 (m, 5H), 7.25–7.21 (m, 2H), 7.14–7.12 (m, 1H), 6.16 (d, *J*=8.4 Hz, 1H), 4.50–4.48 (m, 1H), 3.25–3.20 (m, 2H), 1.67–1.55 (m, 3H), 0.93–0.90 (m, 6H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 166.9, 136.2, 134.5, 131.3, 129.5, 129.0, 128.4, 126.8, 126.2, 47.6, 42.7, 39.2, 25.0, 22.8, 22.2; HRMS-ESI *m/z* calcd for $C_{19}H_{23}NOS+Na^+$ 336.1392, found 336.1389.

4.2.4. (*S*)-*N*-(1-Phenyl-3-(phenylthio)propan-2-yl)-benzamide **3c**

Yield 70%; white solid; mp 151–153 °C; $[\alpha]_D^{20}$ +26 (*c* 1.0, CH_2Cl_2); ^1H NMR ($CDCl_3$, 400 MHz) δ 7.54 (d, *J*=8.0 Hz, 2H), 7.40–7.16 (m, 13H), 6.24 (d, *J*=8.4 Hz, 1H), 4.61–4.58 (m, 1H), 3.19–3.05 (m, 4H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 166.2, 137.1, 135.6, 134.2, 131.4, 129.5, 129.4, 129.1, 128.8, 128.6, 128.4, 126.7, 126.4, 50.5, 38.8, 36.9; HRMS-ESI *m/z* calcd for $C_{22}H_{21}NOS+Na^+$ 370.1236, found 370.1234.

4.2.5. (*S*)-*N*-(1-(2-Chlorophenylthio)-3-methylbutan-2-yl)-benzamide **3d**

Yield 68%; white solid; mp 116–118 °C; $[\alpha]_D^{20}$ +49 (*c* 0.5, CH_2Cl_2); ^1H NMR ($CDCl_3$, 400 MHz) δ 7.74 (d, *J*=7.2 Hz, 2H), 7.54–7.44 (m, 4H), 7.38 (d, *J*=8.0 Hz, 1H), 7.24–7.22 (m, 1H), 7.16–7.14 (m, 1H), 6.24 (d, *J*=8.0 Hz, 1H), 4.32–4.25 (m, 1H), 3.36–3.27 (m, 2H), 3.24–3.15 (m, 1H), 1.00–0.96 (m, 6H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 167.3, 135.1, 134.5, 131.4, 129.9, 129.7, 128.5, 127.3, 127.1, 126.8, 54.0, 35.8, 30.5, 19.5, 18.4; HRMS-ESI *m/z* calcd for $C_{18}H_{20}NOClS+Na^+$ 356.0846, found 356.0844.

4.2.6. (*S*)-*N*-(1-(4-Methoxyphenylthio)-3-methylbutan-2-yl)-benzamide **3e**

Yield 76%; white solid; mp 95–97 °C; $[\alpha]_D^{20}$ +77 (*c* 0.5, CH_2Cl_2); ^1H NMR ($CDCl_3$, 400 MHz) δ 7.64 (d, *J*=6.8 Hz, 2H), 7.47–7.35 (m, 5H), 6.77 (d, *J*=8.4 Hz, 2H), 6.17 (d, *J*=8.8 Hz, 1H), 4.17–4.13 (m, 1H), 3.73 (s, 3H), 3.12–3.10 (m, 2H), 2.08–2.03 (m, 1H), 0.96–0.88 (m, 6H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 167.1, 159.0, 134.7, 133.4, 131.2, 128.3, 126.7, 126.1, 114.7, 55.1, 54.6, 38.9, 30.8, 19.2, 18.4; HRMS-ESI *m/z* calcd for $C_{19}H_{23}NO_2S+Na^+$ 352.1341, found 352.1340.

4.2.7. (*S*)-4-tert-Butyl-*N*-(3-methyl-1-(phenylthio)butan-2-yl)-benzamide **3f**

Yield 75%; white solid; mp 119–121 °C; $[\alpha]_D^{20}$ +62 (*c* 0.5, CH_2Cl_2); ^1H NMR ($CDCl_3$, 400 MHz) δ 7.60–7.55 (m, 2H), 7.41–7.37 (m, 4H), 7.25–7.18 (m, 3H), 6.13 (d, *J*=8.4 Hz, 1H), 4.24–4.20 (m, 1H), 3.24–3.22 (m, 2H), 2.08–2.07 (m, 1H), 1.32 (s, 9H), 0.99–0.95 (m, 6H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 167.1, 154.8, 132.8, 131.8, 129.7, 129.2, 126.6, 126.3, 125.4, 54.3, 37.1, 34.8, 31.1, 30.8, 19.4, 18.3; HRMS-ESI *m/z* calcd for $C_{22}H_{29}NOS+Na^+$ 378.1862, found 378.1859.

4.2.8. (*S*)-*N*-(3-Methyl-1-(phenyltellanyl)butan-2-yl)-benzamide **4**

Yield 52%; yellow solid; mp 79–81 °C; $[\alpha]_D^{20}$ +55 (*c* 1.0, CH_2Cl_2); ^1H NMR ($CDCl_3$, 400 MHz) δ 7.72–7.70 (m, 2H), 7.61–7.58 (m, 2H), 7.45–7.11 (m, 6H), 6.18 (d, *J*=8.4 Hz, 1H), 4.17–4.13 (m, 1H), 3.26 (dd, *J*=12.4 Hz, *J*=6.5 Hz, 1H), 3.21 (dd, *J*=12.4 Hz, *J*=4.7 Hz, 1H), 1.95–1.89 (m, 1H), 0.96 (d, *J*=6.7 Hz, 3H), 0.92 (d, *J*=6.7 Hz, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 166.9, 138.4, 134.6, 131.2, 129.2, 128.4, 127.7, 126.8, 111.1, 55.1, 33.3, 19.3, 18.5, 14.5; HRMS-ESI *m/z* calcd for $C_{18}H_{21}NOTe+Na^+$ 420.0577, found 420.0565.

4.3. General procedure for the palladium-catalyzed asymmetric allylic alkylation

Under an argon atmosphere, a solution of $[Pd(\eta^3\text{-}C_3H_5)Cl]_2$ (2.5 mol %) and chiral ligand (5 mol %) in CH_2Cl_2 (2 mL) was stirred for 30 min at room temperature. Subsequently, a solution of *rac*-1,3-diphenyl-2-propenyl acetate (0.5 mmol), dialkyl malonate (1.5 mmol), *N*,*O*-bis(trimethylsilylacetamide) (BSA) (1.5 mmol), and KOAc (cat. quantity) was added. The resulting solution was stirred for 24 h. The mixture was quenched with a saturated NH_4Cl solution, extracted with CH_2Cl_2 and the combined organic fractions were collected, dried over $MgSO_4$, and filtered. The solvent was removed in vacuo yielding the respective alkylated products **7a–d**, which were purified by flash chromatography.

Acknowledgements

The authors gratefully acknowledge CNPq, CAPES, and FAPERGS for financial support. F.V. thanks CNPq for a Ph.D. fellowship.

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