An Asymmetric Organocatalytic Quadruple Domino Reaction Employing a Vinylogous Friedel–Crafts/Michael/Michael/Aldol Condensation Sequence

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Abstract  An organocatalytic quadruple cascade initiated by a Friedel–Crafts-type reaction is described. The (S)-diphenylprolinol trimethylsilylether catalyzed reaction yields highly functionalized cyclohexenecarboxaldehydes bearing a 1,1-bis[(dialkylamino)phenyl]ethene moiety and three contiguous stereogenic centers. The reaction tolerates various functional groups and all products are obtained with very good diastereoselectivity and with virtually complete enantiomeric excess.

Key words  organocatalysis, domino reaction, quadruple cascade, asymmetric catalysis, alkenylation

In contemporary organic chemistry, organocatalyzed domino reactions are widely regarded as powerful synthetic tools that are increasingly used in the synthesis of biologically active compounds, such as pharmaceuticals and agrochemicals.1 They are of particular interest due to their ability to form complex molecules in a highly stereoselective manner in one-pot procedures.2,3 Secondary amines, such as proline and its derivatives or imidazolidinones, are well-suited catalysts for this type of reaction due to their iminium and enamine activation modes.4 Several simple,5 triple,6 and quadruple7 cascades have been reported so far.

One appealing and synthetically useful organic framework is the cyclohexene building block, which can be prepared by asymmetric amine-catalyzed domino reactions. Its enantioselective synthesis is well explored due to its inherent synthetic and biological importance.8 1,1-Bis(aryl)alkenes have been shown to be effective nucleophiles for addition to aldehydes9 affording bisallylic adducts through Knoevenagel-type 1,2-additions and conjugate additions to enones [Scheme 1 (1) and (2)].10 Similar to the well-studied typical enamine reactivity, the nucleophilicity of these electron-rich alkenes originates from an electron-donating phenylogous dialkylamino functionality.

![Scheme 1 Examples of organocatalytic alkenylation reactions](image-url)
This amino styrene motif has been successfully applied in the field of organic electronics and serves as an important building block for a number of leuco dyes.

In addition to these aniline-derived nucleophiles, there is precedence for electron-rich styrene derivatives to undergo conjugate addition to β-silyl enones [Scheme 1 (3)].

There have also been reports of oxa-Michael, aza-Michael, Michael, and Friedel–Crafts-type reactions for the initiation of quadruple cascades. To the best of our knowledge there are no reports of a quadruple cascade initiated by a vinylogous Friedel–Crafts-type reaction.

Herein we report an organocatalytic quadruple cascade reaction initiated by a vinylogous Friedel–Crafts-type reaction of electron-rich arenes. The thus-formed aniline derivatives feature three contiguous stereocenters and can be obtained in high yields and stereoselectivities in a single one-pot operation.

As can be seen from the retrosynthetic analysis in Scheme 2, after addition of the donor alkene 1 to the iminium-activated acrolein (2), the enamine intermediate will attack the nitroalkene 3 as a second Michael acceptor. The repetition of the catalytic activation of another molecule of acrolein (2) via iminium and enamine intermediates leads to the highly substituted cyclohexenecarbaldehyde 4 through a Michael/aldol condensation sequence.

### Table 1 Optimization of the Reaction Conditions

<table>
<thead>
<tr>
<th>Entry</th>
<th>Catalyst</th>
<th>Additive</th>
<th>Solvent</th>
<th>Yield (%)</th>
<th>ee (%)</th>
<th>dr</th>
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<tbody>
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<td>A</td>
<td>–</td>
<td>CHCl₃</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>–</td>
<td>CHCl₃</td>
<td>40</td>
<td>&gt;99</td>
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<tr>
<td>3</td>
<td>C</td>
<td>–</td>
<td>CHCl₃</td>
<td>5</td>
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<td>–</td>
</tr>
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<td>4</td>
<td>D</td>
<td>–</td>
<td>CHCl₃</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<tr>
<td>5</td>
<td>B</td>
<td>PhCO₂H</td>
<td>CHCl₃</td>
<td>50</td>
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<td>10:1</td>
</tr>
<tr>
<td>6</td>
<td>B</td>
<td>4-MeC₆H₄CO₂H</td>
<td>CHCl₃</td>
<td>38</td>
<td>&gt;99</td>
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<tr>
<td>7</td>
<td>B</td>
<td>4-O₂NC₆H₄CO₂H</td>
<td>CHCl₃</td>
<td>49</td>
<td>&gt;99</td>
<td>8:1</td>
</tr>
<tr>
<td>8</td>
<td>B</td>
<td>PhCO₂H</td>
<td>THF</td>
<td>traces</td>
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<td>–</td>
</tr>
<tr>
<td>9</td>
<td>B</td>
<td>PhCO₂H</td>
<td>toluene</td>
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<td>10</td>
<td>B</td>
<td>PhCO₂H</td>
<td>CH₂Cl₂</td>
<td>34</td>
<td>&gt;99</td>
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<tr>
<td>11*</td>
<td>B</td>
<td>PhCO₂H</td>
<td>CHCl₃</td>
<td>69</td>
<td>99</td>
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<tr>
<td>12f</td>
<td>B</td>
<td>PhCO₂H</td>
<td>CHCl₃</td>
<td>63</td>
<td>99</td>
<td>14:1</td>
</tr>
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</table>

* Reaction conditions: 1-mmol scale using 1a (1 equiv), 2 (5 equiv), 3a (1.1 equiv), additive (20 mol%), catalyst (20 mol%), solvent (3 mL).

* Yield of the isolated product 4a after flash column chromatography.

* Determined by HPLC on a chiral stationary phase.

* Determined by 1H NMR.

* A ratio of 1.5:1.0 of 1a/3a was used.

* A ratio of 2.0:1.0 of 3a/1a was used.
1,1-Bis[4-(dimethylamino)phenyl]ethene (1a), acrolein (2), and β-nitrostyrene (3a) were chosen as test substrates. Initially, the reaction was performed with the electron-rich alkene 1a (1 equiv), β-nitrostyrene (3a, 1.1 equiv), and catalyst B (20 mol%) in chloroform (0.33 M) with the addition of acrolein (2, 5 equiv) on a 1-mmol scale at 0 °C. Under these conditions the desired domino product 4a was obtained in 40% yield with an enantioselectivity of 99% ee (Table 1, entry 2). In order to find the most suitable catalyst for this reaction, we tested several secondary amines known to act as efficient catalysts for iminium activation. It turned out that only the proline-derived trimethylsilyl ether B afforded the domino product in acceptable amounts, whereas the other catalysts failed to promote the reaction (entries 1, 3, and 4). After that, several acidic additives were screened in order to test them for a possible positive influence on the reactivity. While the use of p-toluic acid gave a very similar result, the yield increased when benzoic acid or 4-nitrobenzoic acid were utilized. In contrast to 4-nitrobenzoic acid,

Table 2  Scope of the Reaction

<table>
<thead>
<tr>
<th>Product</th>
<th>R¹</th>
<th>R²</th>
<th>Yield (%)</th>
<th>ee (%)</th>
<th>dr</th>
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<tbody>
<tr>
<td>4a</td>
<td>Me</td>
<td>Ph</td>
<td>69</td>
<td>99</td>
<td>10:1</td>
</tr>
<tr>
<td>4b</td>
<td>Me</td>
<td>4-MeC₆H₄</td>
<td>47</td>
<td>&gt;99</td>
<td>12:1</td>
</tr>
<tr>
<td>4c</td>
<td>Me</td>
<td>4-MeOC₆H₄</td>
<td>53</td>
<td>&gt;99</td>
<td>14:1</td>
</tr>
<tr>
<td>4d</td>
<td>Me</td>
<td>2-ClC₆H₄</td>
<td>50</td>
<td>&gt;99</td>
<td>14:1</td>
</tr>
<tr>
<td>4e</td>
<td>Me</td>
<td>5-methyl-2-furyl</td>
<td>45</td>
<td>99</td>
<td>20:1</td>
</tr>
<tr>
<td>4f</td>
<td>Me</td>
<td>2-naphthyl</td>
<td>41</td>
<td>&gt;99</td>
<td>9:1</td>
</tr>
<tr>
<td>4g</td>
<td>Me</td>
<td>2-thienyl</td>
<td>55</td>
<td>&gt;99</td>
<td>20:1</td>
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<tr>
<td>4h</td>
<td>Et</td>
<td>Ph</td>
<td>35</td>
<td>&gt;99</td>
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</tr>
<tr>
<td>4i</td>
<td>Et</td>
<td>4-MeC₆H₄</td>
<td>41</td>
<td>&gt;99</td>
<td>20:1</td>
</tr>
<tr>
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<td>Et</td>
<td>4-MeOC₆H₄</td>
<td>43</td>
<td>&gt;99</td>
<td>20:1</td>
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<tr>
<td>4k</td>
<td>Et</td>
<td>2-ClC₆H₄</td>
<td>45</td>
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<td>9:1</td>
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<tr>
<td>4l</td>
<td>(CH₂)₄</td>
<td>Ph</td>
<td>49</td>
<td>&gt;99</td>
<td>20:1</td>
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<tr>
<td>4m</td>
<td>(CH₂)₅</td>
<td>Ph</td>
<td>30</td>
<td>&gt;99</td>
<td>10:1</td>
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<tr>
<td>4n</td>
<td>(CH₂)₂O(CH₂)₂</td>
<td>Ph</td>
<td>–</td>
<td>–</td>
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</tbody>
</table>

* Reaction conditions: 1-mmol scale using 1 (1.5 equiv), 2 (5 equiv), 3 (1.0 equiv), PhCO₂H (20 mol%), B (20 mol%), CHCl₃ (3 ml).
*b Yield of isolated product.
*c Determined by HPLC on a chiral stationary phase.
*d Determined by 'H NMR.
benzoic acid gave a better diastereoselectivity, while the yields were on a comparable level with 49% and 50%, respectively (entries 5–7). After having evaluated an efficient catalyst system, the influence of the solvent on the outcome of the reaction was investigated. No reaction occurred in toluene, while for tetrahydrofuran only trace amounts of the desired product were obtained. With dichloromethane the yield decreased to 34%, albeit with a better diastereoselectivity of >20:1 (entries 8–10). Subsequently the ratios of the electron-rich alkene 1a and the nitrostyrene 3a were varied and it was found that an excess of nucleophile 1a enhanced the yield to 69% (entries 11 and 12).

With the optimized conditions in hand, the reaction was then performed with different nitroalkenes 3 and alkenes 1 (Table 2). The reaction tolerates various substitutions of the nitrostyrene component. Electron-donating groups as well as electron-withdrawing functionalities could be embedded in the ortho or para position with good results. The yields for these substrates range from 47 to 53%, with superb enantioselectivities of ≥99% ee and diastereoselectivities between 12:1 and 14:1. Additionally, it was possible to perform the reaction with two different heteroaromatic nitroalkenes as well as with the bulkier naphthalene functionality. For the heteroaromatic substrates yields of 45% and 55% were obtained, while the naphthalene substrate gave the lowest yield with the tested nitroalkenes with 41%. The enantioselectivity for all these different nitroalkenes was excellent (99–≥99%). To enhance the scope of the transformation, the reaction was performed with a variety of electron-rich arenes. We showed that not only several aromatic nitroalkenes, but also different nitroalkenes can be utilized. The resulting cyclohexenecarbaldehydes, bearing three contiguous stereogenic centers and a 1,1-bis[4-(dialkylamino)phenyl]ethene moiety, constitute important scaffolds for biologically active compounds as well as in electronics and dyes. All products were obtained in good domino yields, good to very good diastereoselectivities (9:1 to >20:1), and virtually complete enantioselectivities (≥99%).

In conclusion, we have developed a novel and flexible organocatalytic three-component, quadruple domino reaction initiated by a vinylogous Friedel–Crafts-type reaction of electron-rich arenes. We showed that not only several alkenes, but also different nitroalkenes can be utilized. The resulting cyclohexenecarbaldehydes, bearing three contiguous stereogenic centers and a 1,1-bis[4-(dialkylamino)phenyl]ethene moiety, constitute important scaffolds for biologically active compounds as well as in electronics and dyes. All products were obtained in good domino yields, good to very good diastereoselectivities (9:1 to >20:1), and virtually complete enantioselectivities (≥99%).

Unless otherwise noted, all commercially available compounds were used without further purification. Preparative column chromatography was carried out with Sil G-25 UV254 from Macherey & Nagel, particle size 0.040–0.063 mm (230–240 mesh, flash). Visualization of the developed TLC plates was performed with UV irradiation (254 nm) and with vanillin stain. Optical rotations were measured on a Perkin-Elmer 241 polarimeter. Mass spectra were recorded on a Finnigan SQU7000 (EI 70 eV) spectrometer and HRMS on a Thermo Fishier Scientific Orbitrap XL spectrometer. IR spectra were recorded on a Perkin-Elmer FT-IR Spectrum 100 using an ATR unit. 1H and 13C NMR spectra were recorded at r.t. on Varian Mercury 600 or Inova 400 instruments with TMS as an internal standard. Analytical HPLC was performed with...
performed on a Hewlett-Packard 1100 Series instrument using chiral stationary phases (Daicel AD, Daicel AS, Daicel IA, Daicel OD, Daicel OJ, or Chiralpak IC). Acrolein was purified by distillation and the vi-

Quadruple Domino Reaction; General Procedure

Under an atmosphere of argon, nitroalkene 1 (1 mmol), catalyst B (20 mol%), benzoic acid (20 mol%), and 1,1-bis[4-(dialkylamino)phenyl]ethene 1 (1.5 mmol) were dissolved in CHCl₃ (2 mL) at 0 °C and then treated with a solution of acrolein (2, 5 mmol) in CHCl₃ (1 mL). After 1 d the mixture was concentrated under reduced pressure and the crude product was purified by flash chromatography to afford 4 as a yellowish oil or solid.

(15S,26S)-6-(3,3-Bis[4-dimethylamino]phenyl)allyl)-2-nitro-1,2,3,6-tetrahydrobiphenyl-4-carbaldehyde (4a)

Flash chromatography (n-pentane–Et₂O, 1:1) gave 4a as a yellow oil; yield: 246 mg (47%); 99% ee [HPLC: (S,S)-Whelk O1]; Rₛ = 0.28 (n-pentane–Et₂O, 1:1); [α]₀²⁰ = +100.8 (c 0.97, CHCl₃).

IR (ATR): 2894, 2825, 2215, 2182, 2072, 1980, 1890, 1722, 1683, 1606, 1546, 1516, 1453, 1353, 1250, 1168, 1127, 1032, 945, 908, 816, 729, 665 cm⁻¹.

1H NMR (600 MHz, CDCl₃): δ = 9.54 (s, 1 H, CHO), 7.12 (d, J = 8.8 Hz, 2 H, CH₉), 7.01 (d, J = 8.8 Hz, 3 H, CH₉a), 6.94 (d, J = 8.8 Hz, 2 H, CH₉b), 6.80 (d, J = 8.8 Hz, 2 H, CH₉c), 6.60 (d, J = 8.8 Hz, 2 H, CH₉d), 6.64 (d, J = 8.8 Hz, 2 H, CH₉e).

13C NMR (151 MHz, CDCl₃): δ: 135.9, 134.5, 134.5, 130.9, 130.5, 130.1, 129.0, 128.0, 127.8, 127.7, 127.0, 121.0, 112.0, 83.3, 46.7, 40.9, 40.5, 33.6, 23.8.

HRMS: m/z [M + H⁺] calcd for C₁₃H₁₈N₂O: 201.2862; found: 201.2838.

(15S,26S)-6-(3,3-Bis[4-dimethylamino]phenyl)allyl)-2'-chloro-1,2,3,6-tetrahydrobiphenyl-4-carbaldehyde (4d)

Flash chromatography (n-pentane–Et₂O, 1:1) gave 4d as a yellow oil; yield: 272 mg (50%); 99% ee [HPLC: (S,S)-Whelk O1]; Rₛ = 0.37 (n-pentane–Et₂O, 1:1); [α]₀²⁰ = +183.4 (c 1.02, CHCl₃).

IR (ATR): 3347, 1890, 2807, 2215, 2173, 2079, 1976, 1888, 1723, 1682, 1606, 1520, 1477, 1440, 1352, 1219, 1164, 1048, 945, 909, 816 cm⁻¹.

1H NMR (400 MHz, CDCl₃): δ = 9.74 (d, J = 7.8, 1.5 Hz, 1 H, CH₉), 7.26–7.17 (m, 2 H, CH₉), 7.10 (d, J = 8.8 Hz, 2 H, CH₉), 7.07–7.03 (m, 1 H, CH₉), 7.00 (s, 1 H, CH₉), 6.91 (d, J = 8.8 Hz, 2 H, CH₉b), 6.65–6.61 (m, 4 H, CH₉c), 5.82 (dd, J = 8.8, 6.3 Hz, 1 H, =CH), 5.10–5.06 (m, 1 H, CH₉O, 3.69–3.64 (m, 1 H, CH₉P), 3.29 (d, 1 H, CH₉), 2.97 (s, 6 H, NCH₃), 2.94 (s, 6 H, NCH₃), 2.80–2.70 (m, 2 H, CH₂), 2.49–2.40 (m, 1 H, CH₂), 2.24–2.14 (m, 1 H, CH₂).

HRMS: m/z [M + H⁺] calcd for C₁₃H₁₈N₂OCl: 544.2367; found: 544.2363.

(3S,4R,5S)-3-(3,3-Bis[4-dimethylamino]phenyl)allyl)-4-(5-methylfuranyl-2-yl)-5-nitrocyclohex-1-ene-1-carbaldehyde (4e)

Flash chromatography (n-pentane–Et₂O, 1:1) gave 4e as a yellow oil; yield: 231 mg (45%); 99% ee [HPLC: (S,S)-Whelk O1]; Rₛ = 0.35 (n-pentane–Et₂O, 1:1); [α]₀²⁰ = +101.9 (c 0.99, CHCl₃).

IR (ATR): 3350, 2891, 1808, 2328, 2248, 2087, 1890, 1729, 1684, 1606, 1547, 1520, 1479, 1442, 1353, 1271, 1218, 1162, 1061, 1023, 908, 815, 730 cm⁻¹.

1H NMR (400 MHz, CDCl₃): δ = 9.50 (s, 1 H, CHO), 7.15 (d, J = 8.8 Hz, 2 H, CH₉), 7.04 (d, J = 8.8 Hz, 2 H, CH₉), 6.90–6.85 (m, 1 H, CH₉), 6.71 (d, J = 8.8 Hz, 2 H, CH₉), 6.65 (d, J = 8.8 Hz, 2 H, CH₉), 5.91–5.86 (m, 2 H, CH₉), 5.86–5.82 (m, 1 H, =CH), 4.73–4.67 (m, 1 H, CH₉O), 3.63 (t,
Flash chromatography (n-pentane–Et2O, 1:1) gave 4f as a yellow oil; yield: 198 mg (35%); [α]D20 = 4.4 Hz, 1 H, =CH), 4.66–4.60 (m, 1 H, CHNO2), 3.95 (t, J = 8.8 Hz, 2 H, CHAr), 3.56–3.52 (m, 1 H, CH-naphthyl), 2.97 (s, 6 H, NCH3), 2.94 (s, 6 H, NCH3), 2.87–2.74 (m, 2 H, CH2), 2.52–2.47 (m, 1 H, CH2).


Flash chromatography (n-pentane–Et2O, 1:1) gave 4g as a yellow oil; yield: 229 mg (41%); ≥99% ee [HPLC (S,S)-Whelk O1]; Rf = 0.24 (n-pentane–Et2O, 1:1); [α]D20 = +42.3 (c 0.93, CHCl3).

IR (ATR): 3060, 1518, 1458, 1359, 1263, 1191, 1078, 1012, 910, 812, 725 cm–1.


Flash chromatography (n-pentane–Et2O, 1:1) gave 4h as a yellow oil; yield: 176 mg (31%); ≥99% ee [HPLC (S,S)-Whelk O1]; Rf = 0.24 (n-pentane–Et2O, 1:1); [α]D20 = +104.0 (c 0.98, CHCl3).

IR (ATR): 3060, 1518, 1458, 1359, 1263, 1191, 1078, 1012, 910, 812, 725 cm–1.

HRMS: m/z [M + H]+ calcd for C26H22N4O4: 491.1869; found: 491.1879.

Flash chromatography (n-pentane–Et2O, 1:1) gave 4i as a yellow oil; yield: 180 mg (32%); ≥99% ee [HPLC (S,S)-Whelk O1]; Rf = 0.24 (n-pentane–Et2O, 1:1); [α]D20 = +127.0 (c 1.01, CHCl3).

IR (ATR): 3060, 1518, 1458, 1359, 1263, 1191, 1078, 1012, 910, 812, 725 cm–1.


Flash chromatography (n-pentane–Et2O, 1:1) gave 4j as a yellow oil; yield: 180 mg (32%); ≥99% ee [HPLC (S,S)-Whelk O1]; Rf = 0.24 (n-pentane–Et2O, 1:1); [α]D20 = +127.0 (c 1.01, CHCl3).

IR (ATR): 3060, 1518, 1458, 1359, 1263, 1191, 1078, 1012, 910, 812, 725 cm–1.


Flash chromatography (n-pentane–Et2O, 1:1) gave 4k as a yellow oil; yield: 180 mg (32%); ≥99% ee [HPLC (S,S)-Whelk O1]; Rf = 0.24 (n-pentane–Et2O, 1:1); [α]D20 = +127.0 (c 1.01, CHCl3).

IR (ATR): 3060, 1518, 1458, 1359, 1263, 1191, 1078, 1012, 910, 812, 725 cm–1.

HRMS: m/z [M + H]+ calcd for C29H28N4O4: 539.2442; found: 539.2442.
(1525.65)-6-(3,3-Bis[4-(diethylamino)phenyl]allyl)-2'-chloro-2-nitro-1,2,3,6-tetrahydropiphenyl-4-carbaldehyde (4k)

Flash chromatography (n-pentane–Et2O, 1:1) gave 4k as a yellow oil; yield: 270 mg (45%); 99% ee [HPLC: (S,S)-Whelk O1]; Rf = 0.52 (n-pentane–Et2O, 1:1); [α]D 20 +156.4 (c 0.92, CHCl3).

IR (ATR): 2970, 2890, 1723, 1683, 1605, 1548, 1516, 1477, 1354, 1345, 1307, 1301, 1298, 1283, 1278, 1274, 1265, 1186, 1111, 1110, 831, 443, 44.2, 42.7, 37.1, 31.8, 26.4, 12.7, 12.6.

MS (EI, 70 eV): m/z (%): 599.5 (1), 416.3 (35), 378.3 (76), 335.3 (100), 322.3 (66), 307.2 (27).

HRMS: m/z [M + H]+ calcd for C38H44N3O3: 590.3296; found: 590.3297.

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Supporting Information

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References


