# [6]Saddlequat: A [6]helquat captured on its racemization pathway

Louis Adriaenssens,<sup>‡</sup><sup>a</sup> Lukáš Severa,<sup>‡</sup><sup>a</sup> Dušan Koval,<sup>a</sup> Ivana Císařová,<sup>b</sup> Marta Martínez Belmonte,<sup>c</sup> Eduardo C. Escudero-Adán,<sup>c</sup> Pavlína Novotná,<sup>d</sup> Petra Sázelová,<sup>a</sup> Jan Vávra,<sup>a</sup> Radek Pohl,<sup>a</sup> David Šaman,<sup>a</sup> Marie Urbanová,<sup>e</sup> Václav Kašička<sup>a</sup> and Filip Teplý<sup>\*a</sup>

<sup>a</sup> Institute of Organic Chemistry and Biochemistry (IOCB), Academy of Sciences of the Czech Republic, v. v. i., Flemingovo nám. 2, Prague 166 10, Czech Republic. Fax: +420-220 183 578; Tel: +420-220 183 412; E-mail: <u>teply@uochb.cas.cz</u>

<sup>b</sup> Department of Inorganic Chemistry, Charles University, Hlavova 2030, 128 40 Prague 2, Czech Republic.

<sup>c</sup> Institute of Chemical Research of Catalonia (ICIQ), Av. Països Catalans 16, 43007 Tarragona, Spain.

<sup>d</sup> Department of Analytical Chemistry, Institute of Chemical Technology, Technická 5, Prague 166 28, Czech Republic.

<sup>e</sup> Department of Physics and Measurements, Institute of Chemical Technology, Prague, Technická 5, Prague 166 28, Czech Republic.

*‡ These authors contributed equally to this work.* 

# **Electronic Supplementary Information**



(P)-[6]helquat

(M)-[6]helquat

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#### 1) General information

Liquids and solutions were transferred via needle and syringe under inert atmosphere unless otherwise stated. Melting points were determined on a Wagner & Munz PolyTherm A micro melting point apparatus and are uncorrected. Thin-layer chromatography (TLC) analysis was performed on silica gel plates (Silica gel 60 F<sub>254</sub>-coated aluminium sheets, Merck, cat. no. 1.05554.0001) and visualized by UV (UV lamp 254/365 nm, Spectroline<sup>®</sup> Model ENF – 240C/FE) and/or chemical staining with KMnO<sub>4</sub> [KMnO<sub>4</sub> (1% aq.), Na<sub>2</sub>CO<sub>3</sub> (2% aq.)]. TLC analysis of dications was achieved using Stoddart's magic mixture<sup>1</sup> (MeOH:NH<sub>4</sub>Cl<sub>aq</sub>(2M):MeNO<sub>2</sub> 70:20:10) as eluent on silica gel plates. Flash chromatography was performed on silica gel 60 (Fluka, cat. no. 60741) with the indicated eluent. If necessary, DMSO was removed from samples using a Labconco evaporator (Refrigerated CentriVap Benchtop Vacuum Concentrator, cat. no. 7310031). Sonication was conducted with a BANDELIN SONOREX sonicator. Chemical shifts are given in  $\delta$ -scale as parts per million (ppm); coupling constants (J) are given in Hertz. NMR spectra were measured on a Bruker Avance 600 (600 MHz for <sup>1</sup>H, 151 MHz for <sup>13</sup>C) or Bruker Avance 400 (400 MHz for <sup>1</sup>H, 100.6 MHz for <sup>13</sup>C) NMR spectrometer. In <sup>1</sup>H and <sup>13</sup>C NMR spectra, chemical shifts are given in ppm: in acetone- $d_6$  the peaks were referenced relative to the solvent residual peak (CHD<sub>2</sub>COCD<sub>3</sub>,  $\delta_H$  = 2.09 ppm) and CD<sub>3</sub>COCD<sub>3</sub> ( $\delta_C$  = 29.80 ppm); in CDCl<sub>3</sub> relative to Me<sub>4</sub>Si signals  $\delta_H = 0.00$  ppm or the solvent peak  $\delta_H = 7.26$  ppm and  $\delta_C = 77.00$  ppm; and DMSO- $d_6 \delta_H = 2.50$ ppm and  $\delta_{\rm C} = 39.50$  ppm. <sup>15</sup>N NMR spectra were referenced to the nitromethane peak ( $\delta_{\rm N} = 0$  ppm). Where indicated, the signal assignments in the NMR spectra are unambiguous; the numbering scheme is arbitrary and is shown in the inserts. Where assigned, all <sup>1</sup>H and <sup>13</sup>C resonance assignments are based on analysis of H,H-COSY; H,H-ROESY; H,C-HSQC and H,C-HMBC spectra. IR spectra were recorded on a Bruker EQUINOX55 (IFS55) spectrometer in CHCl<sub>3</sub>, or as KBr pellets. Abbreviations for intensities of IR bands are as follows: s for strong, vs for very strong, m for medium, w for weak, vw for very weak, br for broad, sh for shoulder. Mass spectral data were obtained at the Mass Spectrometry Facility operated by the Institute of Organic Chemistry and Biochemistry, Academy of Sciences of the Czech Republic, v.v.i. (IOCB ASCR). ESI mass spectra were recorded using a Thermo Scientific LCQ Fleet mass spectrometer equipped with an electrospray ion source and controlled by Xcalibur software. The mobile phase consisted of methanol:water (9:1), flow rate of 200 µL.min<sup>-1</sup>. The sample was dissolved, diluted with the mobile phase and injected using a 5 µL loop. Spray voltage, capillary voltage, tube lens voltage and capillary temperature were 5.5 kV, 5 V, 80 V and 275 °C, respectively. HR MS spectra were obtained with the ESI instrument. Specific rotation values were determined with an Autopol IV (Rudolph Research

Analytical, USA, 2001) polarimeter. Specific rotation  $[\alpha]^{20}_{D}$  was measured in concentration (g/100 mL) and solvent as specified in each case.

# 2) Materials

Demineralized water obtained from the Water Purification Facility at the IOCB ASCR was used unless otherwise stated. Demineralization was accomplished *via* filtration through ion exchange columns (Lewatit S100 for catex column, Lewatit MP500 for anex column) in a demineralization ion exchange station type ID-PP and IDKP (Kavalier, Votice, Czech Republic). Dichloromethane, triethylamine, and toluene were purified *via* distillation under Ar over CaH<sub>2</sub> and were used directly after distillation. Degassed solvents were obtained *via* the freeze-pump-thaw method. The solvent was frozen under Ar, and then thawed under vacuum. This process was repeated ( $3 \times$ ). Finally the thawed solvent was purged with argon. DMSO-*d*<sub>6</sub> was dried over 4 Å molecular sieves. Unless otherwise stated, all other starting materials and reagents were obtained from commercial suppliers and used without further purification.

1-Chloroisoquinoline (Aldrich, 95%, 19493-44-8)

2-Ethynylpyridine (Aldrich, 98%, 1945-84-2)

CuI (Aldrich, 99.999%, 7681-65-4)

10 % Pd/C (Alfa Aesar, 7440-05-3)

Triphenylphosphine (Aldrich, 99 %, T84409)

4-Pentyn-1-ol (Alfa Aesar, 98 %, 5390-04-5)

5-Hexyn-1-ol (Aldrich, 96 %, 302015-5G)

Trifluoromethanesulfonic anhydride (Alfa Aesar, 98%, 658-23-6)

Tris(triphenylphosphine)rhodium(I)chloride, [Rh(PPh<sub>3</sub>)<sub>3</sub>Cl] (Fluka, 97+%, 14694-95-2)

Et<sub>3</sub>N (Alfa Aesar, 99%, 121-44-8)

Pyridine (Alfa Aesar, anhydrous 99.5+%, 110-86-1)

N,N-Dimethylformamide (Aldrich, 99.8+%, 319937)

DMSO (Aldrich, 99+%, 67-68-5)

Acetone, dichloromethane, diethyl ether, hexanes, cyclohexane, ethanol, ethyl acetate, methanol and

toluene were purchased from Penta, Czech Republic (www.pentachemicals.eu) unless noted otherwise.

CDCl<sub>3</sub> (Merck, 99.8%, 102450)

Acetone-d<sub>6</sub> (Merck, 99.9%, 100021)

DMSO- $d_6$  (Euriso-Top, C.E. Saclay, H<sub>2</sub>O<0.02%, 99.80% D, D010H Z0331, 100 mL; with 4 Å molecular sieves added)

Na<sub>2</sub>SO<sub>4</sub> (Riedel-de Haën, anhydrous, 7757-82-6)

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NaOH (Penta, 1310-73-2)

CaH<sub>2</sub> (Alfa Aesar, coarse powder, 7789-78-8)

Celite (Fluka, 512 medium, 91053-39-3)

Sulfated  $\gamma$ -cyclodextrin sodium salt, was obtained from Beckman-Coulter as 20 %wt. solution in water (cat. no. A50924).

Universal pH paper strips for pH 0-12 (Lachner)

Methanol for ECD measurements (Lachner)

Strongly basic anion exchange resin Dowex 1 x 2; 16-100, Cl<sup>-</sup> cycle (Supelco, 13367)

(R,R)-(-)-O,O'-Dibenzoyl-L-tartaric acid (Fluka, 99+%, 33620)

Trifluoromethanesulfonic acid (Fluka, 98+%, 91738)

NH<sub>4</sub>PF<sub>6</sub> (Aldrich, 95+%, 20,113-8)

NaClO<sub>4</sub>.H<sub>2</sub>O (Aldrich, 98%, 31,051-4)

# 3) Procedures and analytical data

Part A: Synthesis of [rac-2][TfO]2	ESI 5-ESI 11
Part B: Synthesis of [rac-5][TfO] <sub>2</sub> and [rac-4][TfO] <sub>2</sub>	ESI 12-ESI 19
Part C: Procedure for obtaining enantiopure $(+)$ -[ $S_a$ , $R_a$ -4][TfO] <sub>2</sub> and $(-)$ -[ $P$ -5][TfO] <sub>2</sub>	ESI 19-ESI 25

Part A: Synthesis of $[rac-2]$ [1fO] <sub>2</sub> ESI 5-ESI	ESI 5-ESI 11
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1-(Pyridin-2-ylethynyl)isoquinoline (6), refs 2,3 CAS: 1137276-01-7



Chemical Formula: C<sub>16</sub>H<sub>10</sub>N<sub>2</sub> Molecular Weight: 230.26

This procedure represents a modified version of protocols published in our previous reports.<sup>2,3</sup> 1-Chloroisoquinoline (505.4 mg, 3.06 mmol, 1 equiv), 10 wt% Pd/C (81.3 mg, 76.4 µmol, 2.5 mol%), powderized PPh<sub>3</sub> (160.3 mg, 611 µmol, 20 mol%), and CuI (29.1 mg, 153 µmol, 5 mol%) were added to a sealable teflon reactor (130 mL). Water (13 mL) followed by Et<sub>3</sub>N (1.36 mL, 9.78 mmol, 3.2 equiv), followed by a second portion of water (13 mL) were added, the reactor's top was screwed on and a septum was placed over a small opening in the top allowing for solvent and gas manipulation. Ar was bubbled through the mixture whilst it stirred for 5 min. 2-Ethynyl pyridine (370 µL, 3.67 mmol, 1.2 equiv) was added and the reaction mixture stirred 10 min under Ar. The septum was removed and the reactor was quickly closed completely with its screw-on seal. The reactor was immersed in an oil bath heated to 120 °C and the reaction mixture was stirred for 45 min. The reaction mixture was then filtered through Celite, and the filtercake was washed with ethyl acetate until all UV detectable compounds had eluted. The organic layer was washed with water  $(1\times)$  and the water wash was extracted with CH<sub>2</sub>Cl<sub>2</sub>  $(3\times)$ . The organics were combined, dried over Na<sub>2</sub>SO<sub>4</sub>, and concentrated *in vacuo*. The resultant residue was purified by flash chromatography on silica gel (2:1 v/v hexane/ethyl acetate). 1-(Pyridin-2ylethynyl)isoquinoline (6) was obtained as a yellow oil in 72 % yield (504 mg, 2.19 mmol). The spectroscopic characterization data were in agreement with our previous reports<sup>2,3</sup> and confirmed the purity of compound 6.

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Pent-4-ynyl trifluoromethanesulfonate (7), refs 2,4





A solution of 4-pentyn-1-ol (1.0 mL, 10.7 mmol, 1 equiv) and dry pyridine (0.84 mL, 10.4 mmol, 0.97 equiv) in dry  $CH_2Cl_2$  (6 mL) was added dropwise *via* syringe to a stirring solution of trifluoromethanesulfonic anhydride (1.85 mL, 11.3 mmol, 1.06 equiv) in dry  $CH_2Cl_2$  (6 mL) at 0 °C under Ar. Upon addition a precipitate of pyridinium triflate formed. The reaction mixture was stirred at 0 °C for 30 min. The reaction mixture was then diluted with water (6 mL). The organic layer was separated, dried over  $Na_2SO_4$ , filtered and concentrated *in vacuo* (300 mbar at 25 °C) to give pent-4-ynyl trifluoromethanesulfonate (7) as a brownish liquid.

*Kugelrohr distillation and storage of alkynyl triflate* 7: This liquid was distilled bulb to bulb in a Kugelrohr apparatus (b.p. 55 °C at 2 mbar) to give pure pent-4-ynyl trifluoromethanesulfonate (7) as a colorless liquid in 84 % yield (1.950 g, 9.03 mmol, d = 1.42). The spectroscopic characterization data of alkynyltriflate 7 were in agreement with our previous report<sup>2</sup> and confirmed the purity (see scans of NMR spectra in section 12 of ESI). The alkynyl triflate 7 was stored over NaHCO<sub>3</sub> in the freezer (-20 °C).

Analytical data for pent-4-ynyl trifluoromethanesulfonate (7), ref. 2

OTf <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>):  $\delta = 1.99-2.09$  (m, 2H); 2.03 (t, J = 2.7 Hz, 1H); 2.39 (td, J = 6.8, 2.7 Hz, 2H); 4.68 (tq, J = 6.1, 0.5 Hz, 2H). <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>):  $\delta = 14.49$ ; 28.01; 70.22; 75.43; 81.13; 118.64 (q, J = 319.6 Hz).

Hex-5-ynyl trifluoromethanesulfonate (8), refs 2,4,5 CAS: 85355-21-1



A solution of hex-5-yn-1-ol (0.50 mL, 4.61 mmol, 1 equiv) and dry pyridine (0.37 mL, 4.57 mmol, 0.99 equiv) in dry  $CH_2Cl_2$  (5 mL) was added dropwise *via* syringe to a stirring solution of trifluoromethanesulfonic anhydride (0.78 mL, 4.70 mmol, 1.02 equiv) in dry  $CH_2Cl_2$  (5 mL) at 0 °C under Ar. Upon addition a precipitate of pyridinium triflate formed. The reaction mixture stirred at 0 °C for 15 min, and was then diluted with water (15 mL). The organic layer was separated and washed with

water (1×), dried over Na<sub>2</sub>SO<sub>4</sub>, filtered and concentrated *in vacuo* (300 mbar at 25 °C) to give hex-5-ynyl trifluoromethanesulfonate (**8**) as a brownish liquid in 79 % yield (0.835 g, 3.63 mmol). The spectroscopic characterization data were in agreement with the literature.<sup>2,5</sup> This procedure has been published previously,<sup>2</sup> however the following distillation on Kugelrohr was not used in our previous report. Furthermore, we were previously unaware of the instability of alkynyltriflate **8**.

*Kugelrohr distillation and storage of alkynyl triflate 8:* Crude compound 8 was distilled bulb to bulb in a Kugelrohr apparatus giving hex-5-ynyl trifluoromethanesulfonate (8) as a colorless liquid. Due to the instability of compound 8 it was immediately transferred to a vial containing NaHCO<sub>3</sub> and cooled to -20 °C without taking time to collect all the material or determine the yield. See scans of NMR spectra in section 12 of ESI. The absence of NaHCO<sub>3</sub> during storage leads to impurities in the follow-up reactions using reagent 8, especially during production of triyne 3 (see below).

#### Analytical data for hex-5-ynyl trifluoromethanesulfonate (8), ref. 2

OTf d = 1.33. <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>):  $\delta$  = 1.62-1.72 (m, 2H); 1.93-2.02 (m, 2H); 1.99 (t, *J* = 2.7 Hz, 1H); 2.28 (td, *J* = 6.8, 2.7 Hz, 2H); 4.59 (t, *J* = 6.3 Hz, 2H). <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>):  $\delta$  = 17.68; 23.88; 28.14; 69.39; 76.90; 82.80; 118.63 (q, *J* = 319.6 Hz).

#### **Cationic diyne salt 9**



Molecular Weight: 460.47

Hex-5-ynyl trifluoromethanesulfonate (8) (51  $\mu$ L, 63 mg, 275  $\mu$ mol, 1.1 equiv) was added dropwise over 5 min to a solution of 1-(pyridin-2-ylethynyl)isoquinoline (6) (57.6 mg, 250  $\mu$ mol, 1 equiv) in dry toluene (2.75 mL) stirring vigorously under Ar at -10 °C. The reaction mixture stirred a further 24 h at -10 °C during which time a light yellow precipitate had formed. The precipitate was isolated *via* filtration and the filter cake was washed with hexane. The solid was collected to give a mixture of regioisomers in a 6:1 ratio favoring the desired cationic diyne product **9**. The crude product was dissolved in 9 mL of a 1:1 mixture of toluene and 2-propanol and warmed gently with a heat gun (maximum temperature 60 °C) to dissolve all the material. The solution was cooled to RT, the system was then sealed with a septum and cooled to 4 °C. After 1 day the desired product had started to crystallize as small yellow needles. The

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crystallization was then cooled to -20  $^{\circ}$ C and kept at this temperature for a further 24 h. The crystals were collected by filtration, washed with a cold 2:1 mixture of toluene and 2-propanol (20 mL), and then with hexane. The crystals were collected and dried to give diyne **9** in a 53 % yield (61.5 mg, 134  $\mu$ mol).



#### Analytical data for cationic diyne salt 9

 $R_f$  [SiO<sub>2</sub>, Stoddart's magic mixture<sup>1</sup>]: 0.71. m.p. 120-122 °C (PhCH<sub>3</sub>/*i*-PrOH). <sup>1</sup>H NMR (600 MHz, acetone-*d*<sub>6</sub>): 1.86-1.92 (m, 2H, H-13); 2.40 (td, *J* = 7.0, 2.7 Hz, 2H, H-14); 2.42 (t, *J* = 2.7 Hz, 1H, H-16); 2.46-2.52 (m, 2H, H-12); 5.33 (t, *J* = 7.7 Hz, 2H, H-11); 7.75 (ddd, *J* = 7.8, 4.8, 1.2 Hz, 1H, H-22); 8.14 (td, *J* = 7.8, 1.7 Hz, 1H, H-23); 8.22 (dt, *J* = 7.8, 1.1 Hz, 1H, H-24); 8.32 (ddd, *J* = 8.3, 6.9, 1.2 Hz, 1H, H-6); 8.41 (ddd, *J* = 8.2, 6.9, 1.2 Hz, 1H, H-5); 8.53

(dt, J = 8.2, 1.1 Hz, 1H, H-4); 8.77 (dd, J = 6.8, 0.8 Hz, 1H, H-3); 8.92 (ddd, J = 4.8, 1.7, 1.0 Hz, 1H, H-21); 8.99 (dq, J = 8.3, 0.9 Hz, 1H, H-7); 9.09 (d, J = 6.8 Hz, 1H, H-2). <sup>13</sup>C NMR (151 MHz, acetone- $d_6$ ): 18.37 (C-14); 26.11 (C-13); 30.54 (C-12); 61.67 (C-11); 70.70 (C-16); 77.14 (C-17); 84.04 (C-15); 111.36 (C-18); 127.15 (C-22); 127.20 (C-3); 129.07 (C-4); 129.90 (C-7); 130.37 (C-24); 130.66 (C-10); 133.66 (C-6); 137.53 (C-2); 137.86 (C-5); 138.05 (C-23); 138.32 (C-9); 140.68 (C-19); 140.85 (C-8); 152.19 (C-21). IR (thin film):  $\tilde{v}$  (cm<sup>-1</sup>) 1029 s; 1154 s; 1223 m; 1261 s. MS (ESI) m/z: 343.4 (100); 311.4 [(M-TfO<sup>-</sup>)<sup>+</sup>] (20). HRMS (ESI) m/z: [(M-TfO<sup>-</sup>)<sup>+</sup>] (C<sub>22</sub>H<sub>19</sub>N<sub>2</sub>) calc.: 311.1543, found: 311.1541.

**Cationic triyne salt 1** 



Chemical Formula: C<sub>29</sub>H<sub>26</sub>F<sub>6</sub>N<sub>2</sub>O<sub>6</sub>S<sub>2</sub> Molecular Weight: 676.65

Pent-4-ynyl trifluoromethanesulfonate (7) (89  $\mu$ L, 114 mg, 523  $\mu$ mol, 4 equiv) stored over NaHCO<sub>3</sub> was added dropwise over 1.5 min to a solution of diyne **9** (60.2 mg, 131  $\mu$ mol, 1 equiv) in dry CH<sub>2</sub>Cl<sub>2</sub> (6 mL) stirred under Ar. The reaction mixture was stirred a further 36 h at 25 °C during which time an orange oily precipitate had formed at the bottom of the flask. The reaction mixture was diluted with water and stirred vigorously until all the precipitate had dissolved. The aqueous layer was separated and washed

with  $CH_2Cl_2$  (3x). Water from the aqueous layer was removed on rotary evaporator (bath temperature < 40 °C) to give trive **1** as an orange oil in 69% yield (61.4 mg, 91µmol).

# Analytical data for cationic triyne salt 1



 $R_f$  [SiO<sub>2</sub>, Stoddart's magic mixture<sup>1</sup>]: 0.49. <sup>1</sup>H NMR (600 MHz, acetone-*d*<sub>6</sub>): 1.83-1.88 (m, 2H, H-13); 2.35 (td, *J* = 7.0, 2.7 Hz, 2H, H-14); 2.41 (t, *J* = 2.7 Hz, 1H, H-16); 2.44 (t, *J* = 2.7, 1H, H-29); 2.48-2.53 (m, 2H, H-12); 2.53-2.65 (m, 4H, H-26&H-27); 5.41 (t, *J* = 7.4 Hz, 2H, H-25); 5.43 (t, *J* = 7.7 Hz, 2H, H-11); 8.31 (ddd, *J* = 8.6, 6.9, 1.1 Hz, 1H, H-6); 8.44 (ddd, *J* = 8.4, 6.9, 1.1 Hz, 1H, H-5); 8.55 (ddd, *J* = 7.4, 6.2, 1.9 Hz, 1H, H-22); 8.58 (dt, *J* = 8.4, 1.0 Hz, 1H, H-4); 8.94 (dd, *J* = 6.8, 0.9 Hz, 1H, H-3); 8.98 (td, *J* = 7.7, 1.4

Hz, 1H, H-23); 9.01 (ddd, J = 8.0, 1.9, 0.6 Hz, 1H, H-24); 9.07 (dq, J = 8.6, 0.9 Hz, 1H, H-7); 9.22 (d, J = 6.8 Hz, 1H, H-2); 9.55 (ddd, J = 6.2, 1.4, 0.6 Hz, 1H, H-21). <sup>13</sup>C NMR (151 MHz, acetone- $d_6$ ): 15.92 (C-27); 18.33 (C-14); 25.96 (C-13); 30.31 (C-26); 30.85 (C-12); 61.60 (C-25); 62.38 (C-11); 70.78 (C-29); 71.88 (C-16); 82.71 (C-28); 84.10 (C-15); 90.51 (C-17); 98.02 (C-18); 129.11 (C-3); 129.18 (C-4); 129.80 (C-7); 131.06 (C-22); 131.18 (C-10); 134.26 (C-6); 135.82 (C-19 & C-24); 138.23 (C-5); 138.33 (C-2); 138.47 (C-9); 138.70 (C-8); 147.09 (C-23); 148.91 (C-21). IR (thin film):  $\tilde{v}$  (cm<sup>-1</sup>) 1027 s; 1153 m; 1223 s; 1251 s; 1514 m; 1616 m; 1706 m. MS (ESI) m/z: 527.1 [(M-TfO<sup>-</sup>)<sup>+</sup>] (40); 377.2 [(M-2TfO<sup>-</sup>H<sup>+</sup>)<sup>+</sup>] (35); 311.1 (80); 297.1 (100); 231.1 (50); 189.1 [(M-2TfO<sup>-</sup>)<sup>2+</sup>] (25); 168 (20). HRMS (ESI) m/z: [(M-TfO<sup>-</sup>)<sup>+</sup>] (C<sub>28</sub>H<sub>26</sub>F<sub>3</sub>N<sub>2</sub>O<sub>3</sub>S) calc.: 527.1611, found: 527.1613. ; [(M-2TfO<sup>-</sup>)<sup>2+</sup>] (C<sub>27</sub>H<sub>26</sub>N<sub>2</sub>) calc.: 189.1043, found: 189.1043.

Racemic helquat [rac-2][TfO]<sub>2</sub>



Molecular Weight: 676.65

A solution of triyne **1** (10.7 mg, 15.8  $\mu$ mol, 1 equiv) in anhydrous de-oxygenated DMF (2.5 mL) was added to a solution of [Rh(PPh<sub>3</sub>)<sub>3</sub>Cl] (1.6 mg, 1.7  $\mu$ mol, 11 mol %) also in anhydrous de-oxygenated

DMF (2.5 mL). Upon addition the solution turns from light yellow to red. The reaction mixture is stirred while heating in an oil bath set to 105 °C for 30 min. The reaction mixture was cooled to 25 °C and then all volatiles were removed *in vacuo*. Water (3 mL) and  $CH_2Cl_2$  (3 mL) were added to the resultant residue, and the mixture was stirred vigorously until all material dissolved. The aqueous layer was separated and washed with  $CH_2Cl_2$  (2×), ethyl acetate (1×). Water from the aqueous layer was removed on a rotary evaporator to give racemic helquat [*rac*-**2**][TfO]<sub>2</sub> as a yellow film in a 98 % yield (10.5 mg, 15.5 µmol). **Analytical data for helquat** [*rac*-**2**][TfO]<sub>2</sub>



 $R_f$  [SiO<sub>2</sub>, Stoddart's magic mixture<sup>1</sup>]: 0.36. <sup>1</sup>H NMR (600 MHz, acetone-*d*<sub>6</sub>): 1.83-1.92 (m, 1H, H-13a); 2.20-2.28 (m, 1H, H-12a); 2.26 (ddd, *J* = 14.0, 12.4, 1.3, 1H, H-14a); 2.27-2.34 (m, 1H, H-22a); 2.29-2.34 (m, 1H, H-13b); 2.63-2.73 (m, 1H, H-12b); 2.68-2.75 (m, 1H, H-21a); 2.91-2.98 (m, 1H, H-22b); 3.20-3.27 (m, 1H, H-14b); 3.20-3.27 (m, 1H, H-21b); 4.97 (bdd, *J* = 13.9, 11.1, 1H, H-11a); 5.13 (td, *J* = 13.4, 5.0, 1H, H-23a); 5.18 (dd, *J* = 13.5, 6.7, 1H, H-23b); 5.38 (ddd, *J* = 13.9, 6.9, 1.4, 1H, H-11b); 7.52 (ddd, *J* = 8.2, 1.5, 0.6, 1H,

H-28); 7.95 (ddd, J = 7.8, 6.1, 1.5, 1H, H-26); 7.97 (ddd, J = 8.6, 6.2, 1.1, 1H, H-6); 7.99 (ddt, J = 8.6, 1.8, 0.7, 1H, H-7); 8.08 (d, J = 8.0, 1H, H-20); 8.11 (d, J = 8.0, 1H, H-19); 8.18 (ddd, J = 8.2, 6.2, 1.8, 1H, H-5); 8.28 (td, J = 8.0, 1.5, 1H, H-27); 8.39 (dt, J = 8.2, 1.1, 1H, H-4); 8.80 (dd, J = 6.9, 0.7, 1H, H-3); 9.15 (ddd, J = 6.1, 1.5, 0.6, 1H, H-25); 9.22 (d, J = 6.9, 1H, H-2). <sup>13</sup>C NMR (151 MHz, acetone- $d_6$ ):  $\delta = 27.62$  (C-13); 28.99 (C-21); 29.60 (C-12); 32.10 (C-14); 33.10 (C-22); 58.65 (C-23); 59.99 (C-11); 128.36 (C-10); 128.38 (C-3); 128.62 (C-7); 128.78 (C-26); 129.01 (C-17); 129.11 (C-4); 130.60 (C-28); 131.49 (C-16); 133.50 (C-6); 135.78 (C-19); 136.15 (C-20); 137.80 (C-5); 138.02 (C-2); 138.72 (C-9); 139.83 (C-15); 145.69 (C-18); 147.04 (C-27); 147.72 (C-25); 152.11 (C-29); 156.39 (C-8). IR (KBr):  $\tilde{v}$  (cm<sup>-1</sup>) 1029 s; 1161 s; 1225 m; 1258 s; 1508 w; 1624 w. MS (ESI) m/z: 527.6 [(M-TfO<sup>-</sup>)<sup>+</sup>] (100); 377.5 [(M-2TfO<sup>-</sup>-H<sup>+</sup>)<sup>+</sup>] (20); 335.4 (40). HRMS (ESI) m/z: [(M-TfO<sup>-</sup>)<sup>+</sup>] (C<sub>28</sub>H<sub>26</sub>F<sub>3</sub>N<sub>2</sub>O<sub>3</sub>S) calc.: 527.1611, found: 527.1612.

Part B: Synthesis of [rac-5][TfO]<sub>2</sub> and [rac-4][TfO]<sub>2</sub>

ESI 12-ESI 19

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This procedure represents a scale-up of a procedure we published previously.<sup>2</sup> Pent-4-ynyl trifluoromethanesulfonate (**7**) (393  $\mu$ L, 503 mg, 2.33 mmol, 1.05 equiv) was added dropwise over 3 min to a solution of 1-(pyridin-2-ylethynyl)isoquinoline (**6**) (510.2 mg, 2.22 mmol, 1 equiv) in dry toluene (30 mL) stirring vigorously under Ar at -10 °C. The reaction mixture stirred a further 48 h at -10 °C during which time a light yellow precipitate had formed. The precipitate was isolated *via* filtration and the filter cake was washed with hexane. The solid was collected to give a mixture of regioisomers in a 6:1 ratio favoring the desired cationic diyne product **10**. The crude product was dissolved in 110 mL of a 1:1 mixture of toluene and 2-propanol and warmed gently with a heat gun (maximum temperature 60 °C) to dissolve all the material. The solution was cooled to RT, the system was then sealed with a septum and cooled to 4 °C. After 1 day the desired product had started to crystallize as small yellow needle clusters. The crystallization was then cooled to -20 °C and kept at this temperature for a further 24 h. The crystals were collected by filtration, washed with a cold 2:1 mixture of toluene and 2-propanol (20 mL), and then with hexane. The crystals were collected and dried to give diyne **10** in a 52% yield (515.9 mg, 1.16 mmol). The spectroscopic characterization data were in agreement with our previous report<sup>2</sup> and confirmed the purity of compound **10** (see scans of NMR spectra in section 12 of ESI).

#### Analytical data for cationic diyne salt 10, ref. 2



 $R_f$  [SiO<sub>2</sub>, Stoddart's magic mixture<sup>1</sup>]: 0.71. m.p. 117-119 °C (PhCH<sub>3</sub>/*i*-PrOH). <sup>1</sup>H NMR (400 MHz, acetone-*d*<sub>6</sub>): 2.47 (t, *J* = 2.6 Hz, 1H); 2.52-2.64 (m, 4H); 5.38 (t, *J* = 7.3 Hz, 2H); 7.70 (ddd, *J* = 7.7, 4.8, 1.3 Hz, 1H); 8.09 (td, *J* = 7.7, 1.7 Hz, 1H); 8.21 (dt, *J* = 7.8, 1.1 Hz, 1H); 8.31 (ddd, *J* = 8.3, 6.9, 1.3 Hz, 1H); 8.42 (ddd, *J* = 8.2, 7.0, 1.3 Hz, 1H); 8.53 (broad d, *J* = 8.2 Hz, 1H); 8.78 (broad d, *J* = 6.7 Hz, 1H); 8.89 (ddd, *J* = 4.8, 1.7, 1.0 Hz, 1H); 8.98 (dq, *J* = 8.4, 0.9 Hz, 1H); 9.09 (d, *J* = 6.8 Hz, 1.5 Hz

1H). <sup>13</sup>C NMR (100 MHz, acetone- $d_6$ ): 16.85; 61.80; 72.35; 77.83; 83.54; 103.25; 127.85; 129.79;

130.61; 131.06; 131.41; 134.37; 138.36; 138.61; 138.71; 139.10; 140.92; 141.43; 150.35; 152.86; one carbon peak likely obscured by (*CD*<sub>3</sub>)<sub>2</sub>CO peak.

#### Cationic triyne salt 3



Chemical Formula:  $C_{29}H_{26}F_6N_2O_6S_2$ Molecular Weight: 676.65

Hex-5-ynyl trifluoromethanesulfonate (8) (830 µL, 1.037 g, 4.51 mmol, 4 equiv) stored in the freezer over NaHCO<sub>3</sub> was added dropwise over 1.5 min to a mixture of 4Å molecular sieves (10 beads of molecular sieves, each 3mm in diameter) and divne 10 (502.5 mg, 1.13 mmol, 1 equiv) in dry CH<sub>2</sub>Cl<sub>2</sub> (20 mL) stirred under Ar. The use of NaHCO<sub>3</sub> for storage of the triflate  $\mathbf{8}$  is essential as its absence leads to impurities during production of trivne 3. The reaction mixture was stirred a further 48 h at 25 °C during which time an orange oily emulsion had formed at the bottom of the flask. To remove the molecular sieves the reaction mixture was filtered leaving the oily product in the flask. CH<sub>2</sub>Cl<sub>2</sub> was added to the flask containing the oily residue and this CH<sub>2</sub>Cl<sub>2</sub> was then passed through the filter containing the molecular sieves and into the previous CH<sub>2</sub>Cl<sub>2</sub> filtrate. This procedure was repeated until no oily residue remained and only the crushed molecular sieves rested in the filter cake and on the walls of the flask. In total 300 mL of CH<sub>2</sub>Cl<sub>2</sub> was required. The filtrate was concentrated in vacuo to a volume of about 50 mL, water was added and the mixture was stirred vigorously until all the material had dissolved. The aqueous layer was separated and washed with  $CH_2Cl_2$  (3x). Water from the aqueous layer was removed on rotary evaporator (bath temperature < 40 °C) to give trivine **3** as an orange oil (628.5 mg). The CH<sub>2</sub>Cl<sub>2</sub> washes were combined and extracted with water. The water extract was washed with CH<sub>2</sub>Cl<sub>2</sub> (3x) and water from the aqueous layer was removed on rotary evaporator (bath temp. < 40 °C) to give a second fraction of trivne **3** as an orange oil (96.4 mg). The two product fractions were combined to give trivne **3** in a 95 % yield (724.9 mg, 1.07 mmol).

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#### Analytical data for cationic triyne salt 3



 $R_f$  [SiO<sub>2</sub>, Stoddart's magic mixture<sup>1</sup>]: 0.49. <sup>1</sup>H NMR (600 MHz, acetone- $d_6$ ): 1.78-1.83 (m, 2H, H-26); 2.31 (td, J = 7.0, 2.7 Hz, 2H, H-27); 2.39 (t, J = 2.7 Hz, 1H, H-29); 2.46-2.51 (m, 2H, H-25); 2.49 (t, J = 2.7 Hz, 1H, H-15); 2.58-2.63 (m, 4H, H-12 & H-13); 5.34 (t, J = 7.7 Hz, 2H, H-24); 5.49 (t, J = 7.2 Hz, 2H, H-11); 8.32 (ddd, J = 8.6, 7.0, 1.2 Hz, 1H, H-6); 8.44 (ddd, J = 8.3, 7.0, 1.2 Hz, 1H, H-5); 8.55 (ddd, J = 7.8, 6.2, 1.8 Hz, 1H, H-21); 8.59 (dt, J = 8.3, 1.0 Hz, 1H, H-4); 8.93 (dd, J = 6.8, 0.8 Hz, 1H,

H-3); 8.98 (td, J = 7.9, 1.4 Hz, 1H, H-22); 9.00 (ddd, J = 7.9, 1.8, 0.5 Hz, 1H, H-23); 9.06 (dq, J = 8.6, 0.9 Hz, 1H, H-7); 9.21 (d, J = 6.8 Hz, 1H, H-2); 9.56 (ddd, J = 6.2, 1.4, 0.5 Hz, 1H, H-20).<sup>13</sup>C NMR (151 MHz, acetone- $d_6$ ):16.04 (C-13); 18.28 (C-27); 25.83 (C-26); 30.28 (C-12); 30.70 (C-25); 61.66 (C-11); 62.22 (C-24); 70.75 (C-29); 71.85 (C-15); 83.95 (C-28); 88.05 (C-14); 90.36 (C-16); 98.18 (C-17); 129.20 (C-4); 129.08 (C-3); 129.76 (C-7); 131.09 (C-21); 131.18 (C-10); 134.30 (C-6); 135.51 (C-18); 135.86 (C-23); 138.30 (C-5); 138.43 (C-2); 138.75 (C-9); 138.80 (C-8); 146.92 (C-22); 148.70 (C-20). IR (thin film):  $\tilde{v}$  (cm<sup>-1</sup>) 1029 s; 1156 m; 1224 m; 1257 s; 1515 w; 1616 w. MS (ESI) m/z: 559.2 (30); 527.2 [(M-TfO<sup>-</sup>)<sup>+</sup>] (15); 409.2 (50); 395.2 (100); 329.2 (45); 297.1 (90); 196.1 (20); 160.1 (20). HRMS (ESI) m/z: [(M-TfO<sup>-</sup>)<sup>+</sup>] (C<sub>28</sub>H<sub>26</sub>F<sub>3</sub>N<sub>2</sub>O<sub>3</sub>S) calc.: 527.1611, found: 527.1608. ; [(M-2TfO<sup>-</sup>)<sup>2+</sup>] (C<sub>27</sub>H<sub>26</sub>N<sub>2</sub>) calc.: 189.1043, found: 189.1043.

#### Racemic helquat [rac-5][TfO]<sub>2</sub>



Chemical Formula: C<sub>29</sub>H<sub>26</sub>F<sub>6</sub>N<sub>2</sub>O<sub>6</sub>S<sub>2</sub> Molecular Weight: 676.65

A solution of triyne **3** (30.2 mg, 44.6  $\mu$ mol, 1 equiv) in anhydrous de-oxygenated DMF (8 mL) was added to a solution of [Rh(PPh<sub>3</sub>)<sub>3</sub>Cl] (5.2 mg, 5.6  $\mu$ mol, 12.5 mol%) also in anhydrous de-oxygenated DMF (8 mL). Upon addition the solution turns from light yellow to dark red. The reaction is stirred while heating in an oil bath set to 110 °C for 2 h. The reaction mixture was cooled to 25 °C and then all volatiles

were removed *in vacuo*. Water (3 mL) and CH<sub>2</sub>Cl<sub>2</sub> (3 mL) were added to the resultant residue, and the mixture was stirred vigorously until all material dissolved. The aqueous layer was separated and washed with CH<sub>2</sub>Cl<sub>2</sub> (3×). Water from the aqueous layer was removed on rotary evaporator to give a yellow film. This film contained [*rac*-4][TfO]<sub>2</sub> and [*rac*-5][TfO]<sub>2</sub> in ratio 2.2:1 (see NMR spectrum below). THF (1 mL) was added to the film and the mixture contained in a round bottom flask was immersed in an ultrasonic bath, and sonicated to give a mixture of a yellow THF solution and a yellow powderous precipitate. The THF solution was separated from the precipitate by centrifugation followed by decantation. The THF wash procedure was repeated 2× and then the same wash was performed with EtOAc 1×. The remaining precipitate with acetone (1x) gave pure helquat [*rac*-5][TfO]<sub>2</sub> in 14 % yield (4.2 mg, 6.2 µmol).



Aromatic region of NMR spectrum of crude mixture  $[rac-4][TfO]_2 : [rac-5][TfO]_2 = 2.2:1$ . For full NMR spectra scans of the purified constituents (4 and 5), see the NMR section.

#### Analytical data for helquat [rac-5][TfO]<sub>2</sub>



 $R_f$  [SiO<sub>2</sub>, Stoddart's magic mixture<sup>1</sup>]: 0.29. m.p. = 337-339 °C (Me<sub>2</sub>CO/EtOAc). <sup>1</sup>H NMR (600 MHz, acetone-*d*<sub>6</sub>): 1.99-2.06 (m, 1H, H-21a); 2.20-2.28 (m, 1H, H-22a); 2.20 (ddd, *J* = 14.2, 11.2, 0.8, 1H, H-20a); 2.31-2.37 (m, 1H, H-21b); 2.61-2.67 (m, 1H, H-12a); 2.66-2.72 (m, 1H, H-22b); 2.78 (ddd, *J* = 14.3, 12.1, 7.6, 1H, H-13a); 2.86-2.92 (m, 1H, H-12b); 3.25 (dd, *J* = 14.3, 7.0, 1H, H-13b); 3.27 (dd, *J* = 14.2, 7.6, 1H, H-20b); 4.91 (td, *J* = 13.5, 5.6, 1H, H-11a); 5.20 (dd, *J* = 13.8, 5.9, 1H, H-11b); 5.28 (ddd, *J* = 13.6, 6.5, 1.8, 1H, H-23a); 5.33

(ddd, J = 13.6, 10.7, 1.2, 1H, H-23b); 7.66 (dd, J = 8.0, 1.5, 1H, H-28); 8.007 (ddd, J = 8.6, 6.9, 1.2, 1H, H-6); 8.010 (ddd, J = 8.0, 6.3, 1.5, 1H, H-26); 8.08 (d, J = 8.0, 1H, H-19); 8.106 (bdq, J = 8.6, 1.0, 1H, H-6); 8.010 (ddd, J = 8.0, 6.3, 1.5, 1H, H-26); 8.010 (ddd, J = 8.0, 1H, H-19); 8.106 (bdq, J = 8.6, 1.0, 1H, H-6); 8.010 (ddd, J = 8.0, 6.3, 1.5, 1H, H-26); 8.010 (ddd, J = 8.0, 1H, H-19); 8.106 (bdq, J = 8.0, 1H, H-19); 8.106

7); 8.113 (d, J = 8.0, 1H, H-18); 8.16 (ddd, J = 8.3, 6.9, 1.2, 1H, H-5); 8.17 (td, J = 7.9, 1.5, 1H, H-27); 8.35 (bd, J = 8.3, 1H, H-4); 8.70 (d, J = 6.8, 1H, H-3); 9.08 (d, J = 6.8, 1H, H-2); 9.20 (dd, J = 6.3, 1.5, 1H, H-25). <sup>13</sup>C NMR (151 MHz, acetone- $d_6$ ):  $\delta = 26.93$  (C-21); 29.03 (C-13); 29.89 (C-22); 32.57 (C-20); 33.31 (C-12); 59.34 (C-11); 60.02 (C-23); 127.67 (C-3); 128.17 (C-10); 128.21 (C-7); 129.16 (C-4); 129.35 (C-15); 129.61 (C-26); 131.23 (C-28); 132.00 (C-16); 132.71 (C-6); 134.34 (C-19); 136.70 (C-18); 137.51 (C-5); 137.93 (C-2); 139.35 (C-9); 140.57 (C-14); 145.17 (C-17); 146.29 (C-27); 147.56 (C-25); 152.58 (C-29); 155.53 (C-8). <sup>15</sup>N NMR (60.8 MHz, acetone- $d_6$ ):  $\delta = -173.85$  (N-1); -162.86 (N-24). IR (KBr):  $\nabla$  (cm<sup>-1</sup>) 1032s; 1157s; 1225 m; 1266s; 1512 w; 1624 w. MS (ESI) m/z: 527.5 [(M-TfO<sup>-</sup>)<sup>+</sup>] (100); 437.5 (20); 409.5 (20); 377.4 [(M-2TfO<sup>-</sup>-H<sup>+</sup>)<sup>+</sup>] (30); 189.2 [(M-2TfO<sup>-</sup>)<sup>2+</sup>] (50). HRMS (ESI) m/z: [(M-TfO<sup>-</sup>)<sup>+</sup>] (C<sub>28</sub>H<sub>26</sub>F<sub>3</sub>N<sub>2</sub>O<sub>3</sub>S) calc.: 527.1611, found: 527.1614.

Racemic saddlequat [rac-4][TfO]<sub>2</sub>



A solution of triyne **3** (41.7 mg, 61.6  $\mu$ mol, 1 equiv) in anhydrous de-oxygenated DMF (10 mL) was added to a solution of Rh(PPh<sub>3</sub>)<sub>3</sub>Cl (6.3 mg, 6.8  $\mu$ mol, 11 mol %) also in anhydrous de-oxygenated DMF (10 mL). Upon addition the solution turns from light yellow to dark red. The reaction is stirred while heating in an oil bath set to 105 °C for 30 min. The reaction mixture was cooled to 25 °C and then all volatiles were removed *in vacuo* (bath temperature < 40 °C). Water (3 mL) and CH<sub>2</sub>Cl<sub>2</sub> (3 mL) were added to the resultant residue, and the mixture was stirred vigorously until all material dissolved. The aqueous layer was separated and washed with CH<sub>2</sub>Cl<sub>2</sub> (2×), ethyl acetate (1×). Water from the aqueous layer was removed on rotary evaporator (bath temperature < 40 °C) to give a yellow film. This film contained [*rac*-**4**][TfO]<sub>2</sub> and [*rac*-**5**][TfO]<sub>2</sub> in ratio 4:1 (see NMR spectrum below). THF (1 mL) was added to the film and the mixture of a yellow THF solution and an orange oily precipitate. The THF solution was separated from the precipitate by centrifugation followed by decantation. The THF

precipitate remained in the flask. The THF extracts were combined and the flask containing them was covered and left to stand 15 h at RT. After this time, a light yellow solid precipitate had formed in the solution. The precipitate was removed by centrifugation followed by decantation. The remaining transparent THF solution was concentrated to dryness *in vacuo* (bath temperature < 40 °C) to give racemic saddlequat [*rac*-**4**][TfO]<sub>2</sub> as an oil in a 64 % yield (26.6 mg, 39.3 µmol).



Aromatic region of NMR spectrum of crude mixture  $[rac-4][TfO]_2 : [rac-5][TfO]_2 = 4:1$ . For full NMR spectra scans of the purified constituents (4 and 5), see the NMR section.

#### Analytical data for saddlequat [rac-4][TfO]2



 $R_f$  [SiO<sub>2</sub>, Stoddart's magic mixture<sup>1</sup>]: 0.29. <sup>1</sup>H NMR (600 MHz, acetone- $d_6$ ): 1.78 (dtdd, J = 14.2. 12.5, 6.2, 1.7, 1H, H-21a); 1.86-1.95 (m, 1H, H-22a); 2.12 (ddd, J = 14.0, 12.5, 1.4, 1H, H-20a); 2.17-2.23 (m, 1H, H-21b); 2.36-2.44 (m, 3H, H-12a, H-13a & H-22b); 2.59-2.67 (m, 1H, H-12b); 3.13-3.18 (m, 1H, H-13b); 3.21 (ddd, J = 14.0, 7.1, 1.8, 1H, H-20b); 4.27 (ddd, J = 13.8, 11.5, 0.8, 1H, H-23a); 4.67 (td, J = 13.8, 5.6, 1H, H-11a); 4.73 (ddd, J = 13.8, 6.2, 1.5, 1H, H-23b); 4.97 (dd, J = 13.8, 6.3, 1H, H-11b); 8.05 (d, J = 8.1, 1H, H-19);

8.06 (ddd, J = 7.8, 6.2, 1.5, 1H, H-26); 8.11 (d, J = 8.1, 1H, H-18); 8.24 (ddd, J = 8.5, 6.9, 1.2, 1H, H-6); 8.28 (td, J = 8.0, 1.4, 1H, H-27); 8.35 (dd, J = 8.1, 1.5, 1H, H-28); 8.38 (ddd, J = 8.4, 6.9, 1.1, 1H, H-5); 8.45 (dt, J = 8.4, 1.0, 1H, H-4); 8.54 (dq, J = 8.5, 1.0, 1H, H-7); 8.62 (dd, J = 6.7, 0.8, 1H, H-3); 8.83 (d, J = 6.7, 1H, H-2); 9.13 (dd, J = 6.2, 1.4, 1H, H-25). <sup>13</sup>C NMR (151 MHz, acetone- $d_6$ ):  $\delta = 28.57$  (C-21); 29.27 (C-13); 31.08 (C-22); 32.06 (C-20); 32.15 (C-12); 59.10 (C-23); 59.13 (C-11); 127.78 (C-3); 128.60 (C-15); 128.93 (C-4); 129.01 (C-10); 129.71 (C-26); 130.26 (C-28); 130.39 (C-16); 131.21 (C-7); 132.59 (C-6); 134.19 (C-19); 135.87 (C-18); 137.56 (C-2); 137.88 (C-5); 139.07 (C-14); 139.84 (C-9); 145.21 (C-27); 146.16 (C-17); 148.15 (C-25); 151.32 (C-29); 154.69 (C-8). IR (KBr):  $\tilde{v}$  (cm<sup>-1</sup>) 638 s;

1031s; 1155s; 1263s; 1275s; 1514 w; 1626 w. MS (ESI) m/z: 527.2 [(M-TfO<sup>-</sup>)<sup>+</sup>] (100); 377.2 [(M-2TfO<sup>-</sup>-H<sup>+</sup>)<sup>+</sup>] (15); 307.1 (10). HRMS (ESI) m/z: [(M-TfO<sup>-</sup>)<sup>+</sup>] (C<sub>28</sub>H<sub>26</sub>F<sub>3</sub>N<sub>2</sub>O<sub>3</sub>S) calc.: 527.1611, found: 527.1610.



#### Part C: Procedure for obtaining enantiopure (+)-[S<sub>a</sub>,R<sub>a</sub>-4][TfO]<sub>2</sub> and (-)-[P-5][TfO]<sub>2...</sub>ESI 19-ESI 25

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#### Mixture of two diastereomeric saddlequat salts [rac-4][(R,R)-dibenzoyl tartrate]<sub>2</sub>



#### An anion exchange column was prepared as follows in three steps (ref. 6):

**1.** Strongly basic anion exchange resin in Cl<sup>-</sup> cycle was mixed with water in a column equipped with a teflon tap (column of 1.2 cm diameter, bed height of 12 cm). For uninterrupted smooth flow of liquid through the ion-exchange column either an S0 sinter or a piece of cotton-wool as a plug in the bottom part of the column is recommended. The resin was allowed to swell in distilled water for ca 12 hours.

2. Switching from Cl<sup>-</sup> cycle to OH<sup>-</sup> cycle was performed as follows. A 2 M solution of NaOH<sub>aq</sub> (300 mL) was passed through the resin. Pure water was run through the resin until the eluent passing from the column tested pH neutral. Subsequently, water was expelled from the resin by applying a small overpressure and then MeOH was added filling the void left by the water. All bubbles were removed by stoppering the column and repeatedly turning it gently upside down and right side up, until all resin beads mixed with MeOH and no bubbles remained. The anion exchange resin was now in the OH<sup>-</sup> cycle.

**3.** Switching from OH<sup>-</sup> cycle to dibenzoyl tartrate cycle was done as follows. A 0.2 M solution of (R,R)-(-)-O,O'-dibenzoyl-L-tartaric acid in MeOH (150 mL) was passed through the column, the eluent eventually becoming acidic as the OH<sup>-</sup> sites were consumed. For a rough pH assessment the following method was used: a drop of pure MeOH was spotted on universal pH-paper and, next to it, a drop of the eluting solution was spotted. When the spot belonging to the drop of eluting solution was redder than the

spot belonging to the drop of pure MeOH, the eluting solution was considered acidic. After approximately 125 mL of the acid solution in MeOH had eluted, the column was stoppered and mixed by turning it gently upside down and right side up, so that all the resin beads mixed entirely with the methanolic solution and no bubbles remained. This was very important, as it eliminated residual OH<sup>-</sup> anions which can react with the base sensitive dicationic species. Then the rest of the dibenzoyltartrate solution (25 mL) was passed through the column followed by pure MeOH (80 mL) until the solution eluting from the column was neutral. The anion exchange resin was now ready to use.<sup>6</sup>

A solution of racemic saddlequat [rac-4][TfO]<sub>2</sub> (17.9 mg, 26.5 µmol) in MeOH (12.5 mL) was run through the column packed with ion-exchange resin (preparation see above) which was then washed with 30 mL of methanol to remove all the saddlequat from the column. All volatiles from the resulting MeOH solution of saddlequat were removed *in vacuo* (bath temperature < 40 °C) to give a yellow residue. Acetone was added to the residue and the mixture was sonicated to powderize the saddlequat material. The acetone was then removed *in vacuo* (bath temperature < 40 °C) to give 35.5 mg of a yellow powder that represented the crude mixture of two diasteromeric saddlequat salts  $[rac-4][(R,R)-dibenzoyl tartrate]_2$ .



#### tartrate]<sub>2</sub>

m.p. 148-150 °C.  $[\alpha]_D^{20} = -16.0 \text{ (c} = 0.217 \text{ g/100mL},$ DMSO). <sup>1</sup>H NMR (600 MHz, acetone- $d_6$ ): 1.45-1.58 (m); 1.60-1.69 (m); 1.83 (bt, J = 13.3 Hz); 1.98-2.12 (m); 2.13-2.23 (m); 2.32-2.40 (m); 2.98 (dd, J = 14.0, 6.3 Hz); 3.06 (dd, J = 12.1, 6.8 Hz); 3.85 (dd, J = 13.6, 11.4 Hz); 4.23 (td, J = 13.2, 5.6 Hz); 4.45 (dd, J = 13.6, 6.8 Hz); 4.80 (dd, J = 13.4, 6.3 Hz); 5.71 (s); 7.51-7.54 (m); 7.65-7.68 (m); 7.94-7.97 (m); 8.00 (t, J = 8.1 Hz); 8.06-8.09 (m); 8.15 (td, J = 8.3, 1.5 Hz); 8.28-8.32 (m); 8.35 (dd, J = 8.3, 1.2 Hz); 8.63 (bd, J = 6.8 Hz); 8.90 (d, J = 6.8 Hz); 9.16 (bd, J =6.3 Hz). <sup>13</sup>C NMR (151 MHz, acetone- $d_6$ ):  $\delta = 27.53$ , 27.98, 29.86, 30.69, 30.94, 57.00, 57.23, 71.16, 126.44, 126.96, 127.15, 127.65, 128.47, 128.59, 128.77, 129.05, 129.25, 130.40, 131.27, 132.83, 132.86, 133.59, 134.46,

136.43, 136.74, 137.53, 137.97, 143.78, 144.36, 146.87, 149.41, 152.87, 164.74, 167.50. IR (ATR):  $\tilde{v}$  (cm<sup>-1</sup>) 710vs; 1107m; 1245m; 1716s. MS (ESI) m/z: 735.3 [(M-DBT<sup>-</sup>)<sup>+</sup>] (36); 377.2 [(M-2DBT<sup>-</sup>-H<sup>+</sup>)<sup>+</sup>] (90); 189.1 [(M-2DBT<sup>-</sup>)<sup>2+</sup>] (100). HRMS (ESI) m/z: [(M-DBT<sup>-</sup>)<sup>+</sup>] (C<sub>45</sub>H<sub>39</sub>N<sub>2</sub>O<sub>8</sub>) calc.: 735.27009, found: 735.27007.

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#### Diastereomerically pure saddlequat salt (+)-[S<sub>a</sub>,R<sub>a</sub>-4][(R,R)-dibenzoyl tartrate]<sub>2</sub>



29 mg of the crude mixture of two diasteromeric saddlequat salts [rac-4][(R,R)-dibenzoyl tartrate]<sub>2</sub> (13.3 µmol of each diastereoisomer) was suspended in acetone (2 mL) and this mixture was sonicated for 1 min. The powder was separated from the acetone by centrifugation and decantation. The acetone wash was repeated 4 times giving a pale yellow powder. This pale yellow powder was dissolved in hot (just below boiling) methanol and the resultant solution was allowed to cool to RT. After 20 h fine colorless needles crystallized from the methanolic solution. These crystals were separated by filtration, washed with MeOH (2×) and 1:1 MeOH:EtOH (2×) giving diastereomerically pure saddlequat salt (+)-[ $S_a$ , $R_a$ -4][(R,R)-dibenzoyl tartrate]<sub>2</sub> in a 25 % yield as fine colorless needles (3.7 mg, 3.4 µmol). CE confirmed the purity of the product and estimated the content of the other diastereoisomeric saddlequat salt to be lower than 5 %. The procedure was repeated to accumulate a total of 15 mg of (+)-[ $S_a$ , $R_a$ -4][(R,R)-dibenzoyl tartrate]<sub>2</sub>.

#### Analytical data for the diastereomerically pure saddlequat (+)-[ $S_a$ , $R_a$ -4][(R,R)-dibenzoyl tartrate]<sub>2</sub>:



m.p. 186-187 °C (MeOH/H<sub>2</sub>O, 9 °C).  $[\alpha]_D^{20} = +119.6$  (c = 0.097 g/100mL, DMSO). <sup>1</sup>H NMR (600 MHz, acetone- $d_6$ ): 1.49-1.58 (m); 1.59-1.68 (m); 1.83 (t, J = 12.8 Hz); 2.00-2.11 (m); 2.12-2.22 (m); 2.32-2.37 (m); 2.97 (dd, J = 14.1, 6.3 Hz); 3.05 (dd, J = 12.8, 6.3 Hz); 3.84 (dd, J = 13.5, 11.5 Hz); 4.21 (td, J = 13.5, 4.9 Hz); 4.42 (bdd, J = 13.5, 5.7 Hz); 4.76 (bdd, J

= 13.9, 6.3 Hz); 5.61 (s); 7.44 (bt, *J* = 7.8 Hz); 7.58 (bd, *J* = 7.4 Hz); 7.88 (bd, *J* = 7.2 Hz); 7.91 (d, *J* =

8.0 Hz); 7.76 (ddd, J = 8.0, 6.8, 1.6 Hz); 7.97 (d, J = 8.0 Hz); 8.03-8.07 (m); 8.12 (td, J = 8.0, 1.4 Hz); 8.26-8.30 (m); 8.32 (dd, J = 8.5, 1.5 Hz); 8.59 (bd, J = 6.6 Hz); 8.85 (bd, J = 6.7 Hz); 9.11 (bd, J = 6.3 Hz). <sup>13</sup>C NMR (151 MHz, acetone- $d_6$ ):  $\delta = 27.33$ , 27.87, 29.72, 30.60, 30.82, 56.94, 57.17, 70.55, 126.34, 126.84, 127.04, 127.51, 128.34, 128.41, 128.65, 128.97, 129.44, 130.19, 131.16, 132.69, 133.12, 134.33, 136.23, 136.60, 137.41, 137.87, 143.67, 144.24, 146.69, 149.31, 152.76, 164.59, 167.36. IR (ATR):  $\tilde{v}$  (cm<sup>-1</sup>) 710vs; 1107m; 1245m; 1716s. MS (ESI) m/z: 735.3 [(M-DBT)<sup>+</sup>] (9); 377.2 [(M-2DBT<sup>-</sup>H<sup>+</sup>)<sup>+</sup>] (34); 189.1 [(M-2DBT<sup>-</sup>)<sup>2+</sup>] (100). HRMS (ESI) m/z: [(M-DBT<sup>-</sup>)<sup>+</sup>] (C<sub>45</sub>H<sub>39</sub>N<sub>2</sub>O<sub>8</sub>) calc.: 735.27009, found: 735.26982.

#### Enantiopure saddlequat (+)-[S<sub>a</sub>,R<sub>a</sub>-4][TfO]<sub>2</sub>



Chemical Formula: C<sub>29</sub>H<sub>26</sub>F<sub>6</sub>N<sub>2</sub>O<sub>6</sub>S<sub>2</sub> Molecular Weight: 676.65

#### An anion exchange column was prepared as follows in three steps (ref. 6):

**1.** & **2.** Ion-exchange resin (7 mL bed volume) in a column of 1.2 cm diameter was exchanged to OH<sup>-</sup> cycle (for details, see procedure on page ESI 20). In this particular case, the solvent was not changed for MeOH at the end of the  $2^{nd}$  step!

**3.** Then, a 0.2 M solution of TfOH in water was passed through the column. The solution coming out from the column started to be acidic (universal pH paper test) after using 25 mL of this solution. Overall, 30 mL of this solution were passed through the column and, at the late stage of the exchange the column was stoppered and mixed by turning it gently upside down and right side up, so that all beads of the resin nicely mixed with MeOH and no bubbles remained. This is very important, as residual OH<sup>-</sup> anions can react with helquats. Then, pure water was run through, until the solution eluting from the column was neutral (universal pH paper test).

Then, water was expelled from the resin by applying a small overpressure and MeOH was added filling the void left by the water. All bubbles were removed by mixing the resin with a long needle or by stoppering the column and turning it gently upside down and right side up, so that all resin beads nicely

mixed with MeOH and no bubbles remained. The anion exchange resin was now in TfO<sup>-</sup> cycle and ready to use.<sup>6</sup>

A solution of diastereomerically pure saddlequat (+)-[ $S_a$ , $R_a$ -4][(R,R)-dibenzoyl tartrate]<sub>2</sub> (11.7 mg, 10.7 µmol) in MeOH (10 mL) was run through the above described column loaded with anion exchange resin in TfO<sup>-</sup> cycle. The column was then washed with methanol (20 mL) and the combined methanolic fractions were concentrated to dryness *in vacuo* (bath temperature < 40 °C) to give a colorless residue. The sample was disolved in a mixture of H<sub>2</sub>O and CH<sub>2</sub>Cl<sub>2</sub>. The water layer was washed with CH<sub>2</sub>Cl<sub>2</sub> (3×), ethyl acetate (5×), and concentrated to dryness (bath temperature < 40 °C) to give optically pure saddlequat (+)-[ $S_a$ , $R_a$ -4][TfO]<sub>2</sub> in 55 % yield as a colorless solid (4.0 mg, 5.9 µmol).

#### Analytical data for optically pure saddlequat (+)-[*S<sub>a</sub>*,*R<sub>a</sub>*-4][TfO]<sub>2</sub>:

m.p. 116-118 °C. Specific optical rotation of optically pure saddlequat (+)-[ $S_a$ , $R_a$ -4][TfO]<sub>2</sub> was measured in MeOH, c = 0.129 g/100mL at 20 °C at various wavelengths. The corresponding  $[\alpha]_{\lambda}^{20}$  values are tabulated below:

Wavelength [nm]	$[\alpha]_{\lambda}^{20}$
405	+231
436	+344.2
546	+249.6
589	+213.9
633	+184.5

Optimized preparative procedure to make the sample of optically pure helquat (-)-[*P*-5][TfO]<sub>2</sub> used for the racemization study



(+)-[ $S_a$ , $R_a$ -4][TfO]<sub>2</sub> (7.8 mg, 11.5 µmol) was dissolved in dry DMSO- $d_6$  (0.5 mL). This solution was transferred to an NMR tube and heated to 120 °C for 3 h in an oil bath. NMR analysis showed, that the sample was almost completely converted to helquat with only traces of saddlequat left (saddlequat content was under the detection limit of NMR; <5 % of saddlequat). Chiral CE analysis confirmed that the sample was composed almost exclusively of helquat (-)-[P-5][TfO]<sub>2</sub> (The composition as determined by chiral CE was as follows: 96.5 % of (-)-[P-5][TfO]<sub>2</sub>; 1.5 % saddlequat and less than 2 % of enantiomeric helquat (+)-[M-5][TfO]<sub>2</sub>). Then, DMSO was removed using a Labconco evaporator (45 °C) and the remaining residue was further dried under high vacuum. (-)-[P-5][TfO]<sub>2</sub> was obtained as a colorless oil (7.4 mg, 11 µmol). ECD, UV-vis, FDCD, and fluorescence spectra were recorded with this material (see section 8 of the ESI).

#### Analytical data for the optically pure helquat (-)-[P-5][TfO]<sub>2</sub>

m.p. 339-341 °C (crystals were prepared by slow diffusion of  $(i-Pr)_2O$  into a MeOH solution of the helquat). The specific optical rotation of the optically pure helquat  $(-)-[P-5][TfO]_2$  was measured in MeOH, c = 0.232 g/100mL at 20 °C at various wavelengths. The corresponding  $[\alpha]_{\lambda}^{20}$  values are tabulated below:

Wavelength [nm]	$[\alpha]_{\lambda}^{20}$
405	-980.8
436	-424.0
546	-64.6
589	-35.3
633	-20.7

# 4) Capillary electrophoresis (CE)

Capillary electrophoresis (CE) measurements were carried out in an in-house built device.<sup>7</sup> Briefly, computer controlled high voltage module CZE 2000 (Spellman, Hauppauge, New York, USA) and pneumatic valves were used for delivery of separation voltage and performing capillary filling, flushing and hydrodynamic injection of analytes, respectively. Zones of analytes were detected by UV absorbance at 206 nm. The Clarity data station (DataApex, Prague, Czech Republic) was employed for data acquisition and subsequent analysis. Relative quantitative evaluation of the species in the sample was based on the corrected (migration time normalized) peak areas.<sup>8</sup>

For chiral analysis of the helquat/saddlequat system, internally untreated fused silica capillaries with outer polyimide coating of 50/375  $\mu$ m id/od (Polymicro Technologies, Phoenix, AZ, USA) were used in 29/40 cm effective/total length. A background electrolyte consisted of 22 mM sodium, 35 mM phosphate buffer, pH 2.4, and a chiral selector, 1.5 %wt. (ca 6 mM) sulfated  $\gamma$ -cyclodextrin (Beckman-Coulter, cat. no.

A50924).<sup>9</sup> Samples taken from parallel NMR experiments dissolved in DMSO- $d_6$  were diluted with water to ca 1 – 2 mM concentration and injected into the capillary hydrodynamically, by pressure of 300 – 500 Pa for 3 – 5 s. Separation voltage was –12 kV (*i.e.* cathode at the injection capillary end), at ambient temperature of 22-25°C. The relevant CE charts from monitoring of transformation (+)-[ $S_a$ , $R_a$ -4][TfO]<sub>2</sub> $\rightarrow$ (-)-[P-5][TfO]<sub>2</sub> are in section 6 of this ESI. The CE charts from the racemization study performed with helquat (-)-[P-5][TfO]<sub>2</sub> are in section 9 of this ESI.

# 5) DFT-D calculations

All calculations were carried out on DFT or DFT-D level in Turbomole 6.1.<sup>13,10</sup> The PBE and B3LYP functionals<sup>14,15</sup> have been used throughout. The calculations were performed using expanded Coulomb integrals in an auxiliary basis set, the resolution-of-identity (RI) approximation.<sup>16,17</sup> All the geometry optimisations were carried out using the RI-PBE method and def2-SV(P) basis set *in vacuo* (energy E<sub>1</sub>), identity of minima and transition states (Scheme S1, Summary Table S1) were confirmed by frequency calculations at the same level of theory (correction to Gibbs energy  $E_{ZPE} - RTln(q_{trans}q_{rot}q_{vib})$ ). Single-point energies were then recomputed in larger basis set def2-TZVP,<sup>18</sup> using the B3LYP method, also *in vacuo* (energy E<sub>el</sub>). To account for solvation effects and empirical dispersion correction, single point energy of the stationary point was recomputed in the same level of theory, as for the optimizations and frequency calculations (RI-PBE/def2-SV(P)) using Grimme's empirical correction for dispersion<sup>11,12</sup> and the conductorlike screening model (COSMO) method<sup>19,20</sup> with the dielectric permitivity constant corresponding to DMSO ( $\varepsilon_r = 46.83$ ) (energy E<sub>2</sub>). Both of these methods are implemented in Turbomole 6.1 program package.<sup>13</sup> The Gibbs energy of the stationary point was then calculated as a sum of all described contributions (Eq. (1))

$$\Delta G = E_{el} + (E_2 - E_1) + E_{ZPE} - RT \ln (q_{trans}q_{rot}q_{vib})$$
(1)

where  $E_{ZPE}$  is the zero-point energy, and  $-RT \ln(q_{trans}q_{rot}q_{vib})$  accounts for the entropic terms and the thermal correction to the enthalpy (obtained from the frequency calculation at 373 and 453 K and 1 atm pressure, using an ideal-gas approximation).<sup>21</sup> The Gibbs energy calculated from Eq. (1) is a good approximation to  $\Delta G$  in dilute solution.

The results of this theoretical study are best summarized in the dynamic visual form of the movie we present in the electronic table-of-contents and also Electronic supplementary information. For details on energies and calculated geometries of the individual minima (MIN) and transition states (TS) on the racemization pathway of helquat **5** see Scheme S1, Table S1 and pages ESI 29-ESI 41.

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Scheme S1 Calculated racemization pathway of helquat 5 (Gibbs energies in DMSO at 100 °C). For energies and calculated geometries of the individual minima (MIN) and transition states (TS) see Table S1 and pages ESI 29-ESI 41. Structures corresponding to the isolable species [P-5], [ $S_a$ , $R_a$ -4], and [M-5] and the two key barriers investigated in the experimental part of this work are highlighted in yellow.

Descriptors p, m, and 0 are used to specify the key dihedral angles in the notation of structures on the enantiomerization pathway of helquat [*P*-**5**] (see structures on pages ESI 29-ESI 41). Positive sign of a depicted dihedral angle is denoted as p, negative sign of a dihedral angle is denoted as m, and 0 denotes a dihedral angle which is approximately zero. The order of dihedral angles is specified in an example below (Scheme S2).



Scheme S2

Movie frame	Name of structure	E <sub>1</sub>	E <sub>el</sub>	ΔG
E L/mol DFT	MIN-helquat-pmp-pp	0.0	0.0	0.0
E Lalmost DFT	TS-ррр-рр	33.3	33.2	35.1
E Lalmon OFT	MIN-ppm-pp	12.9	16.2	11.8
E bilmod DFT	TS-0p0-pp	33.3	33.0	35.1
E Lumol DET	MIN-mpp-pp	24.5	27.1	23.3
E Lumol DET	TS-mmp-pp	125.2	133.8	136.9
E Lulmol DET	MIN-mmp-pp	27.7	30.6	32.2
E Lumol DFT	TS-mmm-pp	38.8	40.1	45.2
E bilmod DFT action coordinate	MIN-saddlequat-mpm-pp	13.7	14.4	18.4
E Lalmod DFT	TS-mpm-pp	132.9	144.0	150.2
E La/mol DFT	MIN-mpm-pp	132.2	144.7	137.9
E La/mol DFT	TS-mpm-0p	148.1	162.2	156.6
E kJ/mol DFT	MIN-helquat-mpm-mm	0.0	0.0	0.0

**Table S1**  $E_{el}$ ,  $E_1$  and  $\Delta G$  in kJ/mol,  $\Delta G$  in DMSO at 100°C. Structures corresponding to the isolable species [*P*-5], [*S<sub>a</sub>*,*R<sub>a</sub>*-4], and [*M*-5] studied in the experimental part of this work are highlighted in yellow.

Geometries optimized by ri-PBE/def2-SV(P) in vacuo:

(Structures corresponding to the isolable species [P-5],  $[S_a, R_a-4]$ , and [M-5] investigated in the experimental part of this work are highlighted in yellow.)

M]	N-helquat-pmp-pp	(corresponds	to the	isolated	species	[ <b>P-5</b> ])	

55			
E1	= -1151.2005	<mark>61731</mark>	
С	-0.0000512	0.0016325	-0.0025682
С	-0.0015420	0.0011619	1.4173260
С	1.2335149	-0.0017450	2.0909749
C	-1 3141526	0.0773472	2 1652839
н	1.2470707	-0.0179866	3 1932785
11 11	1.2470707	0.1252772	2 2420067
п	-1.1003009	-0.1333773	3.2430907
п	-2.0073744	-0./100852	1.7957652
C	2.4377783	0.04/9014	1.3848067
C	-1.9803018	1.4661888	2.0046503
H	3.3880533	0.0886813	1.9428572
H	-1.5074775	2.2129107	2.6798315
Η	-3.0491621	1.3999471	2.3018879
С	-1.8521689	2.0194294	0.5762274
Η	-0.8124744	2.3463427	0.3691301
Н	-2.5196713	2.8886004	0.4163200
C	2.4742444	0.0999142	-0.0253655
N	-2.2006825	0.9872073	-0.4383731
C	1 2372241	0.0353550	-0 7257245
$\tilde{c}$	-1 3308637	-0.0368362	-0.6870961
$\frac{c}{c}$	3 8221623	0.2698957	-0.7055269
$\frac{c}{c}$	3 4429763	1.0573101	1.0335433
с ц	3 7300751	0.8844614	1 6206253
и П	4 4620240	0.8612271	-1.0290233
п	4.4039249	0.0015571	-0.0192382
	-4.0382037	1.92/0/32	-0.7600394
	4.5514200	-1.0391130	-1.01/32/1
C H	-3.86/636/	0.0913748	-1.9159563
H	5.6391962	-0.8532802	-1.113/506
H	4.4485892	-1.7395942	-0.1421365
Н	-4.8585425	0.1885764	-2.3864358
С	4.0955118	-1.7788000	-2.2910990
H	4.4923133	-1.2654387	<u>-3.1975707</u>
Н	4.5407477	-2.7978479	-2.3083433
С	2.5764995	-1.9562837	-2.4523892
H	2.3519847	-2.7727200	-3.1677974
H	2.0953916	-2.2061311	<u>-1.4868810</u>
C	-3.0488024	-1.0428754	-2.1758914
N	1.8927896	-0.7430125	-3.0023565
C	-1.7597419	-1.1179500	-1.5211869
C	1.2398451	0.1726877	-2.2071678
С	-3.4775565	-2.1131089	-3.0093467
С	1.9601208	-0.5758822	-4.3563925
Н	-4.4562178	-2.0433560	-3.5106290
н	2,5043787	-1.3560482	-4.9105951
C	-2.6850737	-3 2439531	-3 1590005
C	1 3766374	0 5106976	-4 9956657
н	-3.0309555	-4 0791001	-3 7893824
н	1 4622215	0.6047572	-6.0892993
$\hat{C}$	1.4022215	3 3/83///	2 4712000
	0.6064738	1 4623246	4 2177121
С Ц	0.0904738	1.4023240	2 5550881
n U	-0.0333090	-4.2704324	-2.5550881
п	0.2300730	2.3408390	-4.00/2000
	-0.9849546	-2.3080513	-1.0/483/3
	0.0328498	1.2795241	-2.8319232
H	-0.0496839	-2.416/209	-1.1069961
H	0.143/987	2.0298002	-2.1931501



TS-ppp-pp:	
55	

E1	= -1151.1878	96597	
С	-0.0076645	-0.0588378	0.0204947
С	-0.0403106	-0.0509878	1.4422869
Ċ	1 1768137	-0.0316548	2 1459282
c	-1 3717982	0.0287783	2 1549686
н	1.1616220	-0.0518830	3 2/81622
и П	1.1010220	0.1990559	2 2260140
п ц	-1.2490149	-0.1660336	3.2300140
П	-2.0017280	-0.7310370	1.7013430
C	2.3997755	0.0683596	1.4/22/08
C	-2.0188511	1.4253202	1.9788720
Н	3.3319377	0.1573042	2.0544942
Н	-1.5604765	2.1638267	2.6728918
Η	-3.0976396	1.3696234	2.2403429
С	-1.8372760	1.9848569	0.5585337
Η	-0.7868533	2.2954939	0.3837385
Η	-2.4846334	2.8664152	0.3846081
С	2.4642864	0.1248432	0.0663683
Ν	-2.1748213	0.9650613	-0.4729640
С	1.2454314	-0.0052434	-0.6646831
С	-1.3223416	-0.0796170	-0.6980238
Ċ	3.7653809	0.4907964	-0.6302452
C	-3.3956901	1.0670636	-1.1064271
н	3 5176444	1 2531936	-1 4007420
н	4 3886212	1.03/6819	0.1095521
н	-3 9980544	1.0540017	-0.8/899/3
C	4 6624863	0.6046681	1 2018182
C	2 8150862	0.1140444	2 0058270
С	-5.0159002	0.1149444	-2.0038270
п	5.00/52/9	-0.1090015	-2.2503941
H	5.5545571	-0.7746845	-0.6529737
Н	-4./88548/	0.2384604	-2.50/39/2
C	4.0827739	-2.0006553	-1.5966416
Н	4.7332490	-2.4758154	-2.3622601
Н	4.1600077	-2.6529705	-0.6992838
С	2.6089784	-2.1101081	-2.0406988
Η	2.4611196	-2.9977069	-2.6891929
Η	1.9528876	-2.2293398	-1.1605291
С	-3.0180572	-1.0386496	-2.2429130
Ν	2.0673360	-0.9432098	-2.7962786
С	-1.7530132	-1.1476723	-1.5469671
С	1.3387196	0.0351101	-2.1498735
С	-3.4465717	-2.0959238	-3.0929702
С	2.2875458	-0.8903720	-4.1402134
Н	-4.4061189	-1.9998308	-3.6258018
Н	2.8843326	-1.7133304	-4.5638545
С	-2.6792743	-3.2466873	-3.2194014
C	1 7795318	0 1411356	-4 9228867
н	-3 025/13/18	-4 0714054	-3 8632071
н	1 0862172	0 1523786	6.0042650
C	1.9602172	3 38/7/0/	2 /005832
C	-1.404/140	1 1 4 1 2 4 6 0	-2.4903032
	0.0006440	1.1412400	-4.3041203
п	-0.8780440	-4.32/94/1	-2.330/418
Н	0.39/8916	1.9/52448	-4.8940336
C	-1.0060/88	-2.35//29/	-1.6//5063
C	0.7958740	1.07/1919	-2.9209909
H	-0.0949743	-2.4929417	-1.0776100
Н	0.2341660	1.8704376	-2.4054218



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#### MIN-ppm-pp:

55			
E1	= -1151.1956	32266	
С	0.3339679	1.2910691	-0.2086867
С	0.6882245	2.5541006	-0.7461818
С	-0.3455399	3.4375918	-1.1040934
С	2.1455658	2.9402530	-0.8730104
Н	-0.0951523	4.4166736	-1.5447822
Н	2.2486870	3.8673858	-1.4728892
Н	2.6988592	2.1519444	-1.4318339
C	-1 6799024	3 0914603	-0.8999662
C	2 8066704	3 1487648	0 5116672
н	-2 4659372	3 8140664	-1 1757145
н	2 5355071	4 1408085	0.9350982
н	3 9121382	3 1431703	0.3972001
C	2 3672314	2 0937303	1 5404351
ц	1 3244017	2.0757102	1 8723383
н	3 0167420	2.2754102	2 / 37160/
II C	2.0720727	2.1037352	2.43/1094
U N	-2.0720757	1.8002209	-0.3082093
N C	2.4141331	0.7240918	0.9003900
C	-1.0424780	0.9393837	0.0259207
C	1.400/959	0.3422322	0.0000074
C	-3.303/033	1./03//12	-0.0021853
C II	3.4844839	-0.0831347	1.2849300
H	-3./5/35/0	2.4/86/53	0.8326083
H	-4.09/8163	2.2118612	-0.8/16551
H	4.1876904	0.3255982	2.0256861
С	-4.2589042	0.4439542	0.3565163
С	3.6455114	-1.3207679	0.7071796
Н	-3.8719977	0.0394083	1.3195178
Η	-5.3222572	0.6882102	0.5684645
Η	4.5029024	-1.9461827	1.0015728
С	-4.2373843	-0.6397403	-0.7282532
Η	-4.8377366	-1.5135380	-0.3887172
Η	-4.7206487	-0.2732867	-1.6613237
С	-2.8212740	-1.1111490	-1.1005046
Η	-2.8392985	-2.0546562	-1.6821369
Η	-2.2772127	-0.3496619	-1.6911908
С	2.7385168	-1.7593297	-0.2978451
Ν	-2.0390371	-1.3609324	0.1384254
С	1.6334271	-0.8914619	-0.6454869
С	-1.3020758	-0.3554996	0.7238923
С	2.9159535	-2.9857264	-0.9964082
С	-2.2183993	-2.5633856	0.7557206
Η	3.7548631	-3.6442097	-0.7195458
Н	-2.8315813	-3.2967905	0.2091782
С	2.0621425	-3.3274088	-2.0371479
С	-1.6735367	-2.8354964	2.0049527
Η	2.2168987	-4.2679370	-2.5903439
Н	-1.8446719	-3.8192675	2.4687477
C	1.0089275	-2.4510784	-2.4206636
Ĉ	-0.9379568	-1.8267692	2.6490437
H	0.3773088	-2.7106090	-3.2858612
Н	-0.5224258	-1.9922197	3.6565321
C	0.7908589	-1.2623316	-1.7377182
č	-0 7529421	-0 6020336	1 9978926
й	0.0045618	-0 5688561	-2 0718677
Н	-0.2015477	0.2124103	2.4905174



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55			
E1	= -1151.1878	370282	
С	-0.2517734	-0.2523575	1.2305964
С	-0.4393419	-0.7961656	2.5296558
С	0.6920955	-1.0555949	3.3233775
С	-1.8442813	-0.9789311	3.0596728
Η	0.5593043	-1.5002054	4.3235409
Η	-1.8379480	-1.5984386	3.9797386
Η	-2.4622126	-1.5344745	2.3189144
С	1.9741104	-0.7047081	2.8865252
С	-2.5085682	0.3878026	3.3645547
Н	2.8336348	-0.8518874	3.5615927
Н	-2.1566253	0.7882255	4.3405329
Н	-3.6084087	0.2538003	3.4540148
С	-2.1817387	1.4572753	2.3087725
H	-1.1270140	1.7898817	2.3939064
н	-2.8288135	2.3486656	2.4218488
C	2 1886709	-0 1032688	1 6300007
N	-2 3717000	0.932/329	0.928/671
C	1.0650602	0.9524529	0.9204071
C	1.0050002	0.0398000	0.7003373
C	-1.460/3/4	0.0280073	0.4219437
C	2.5051590	0.4/80840	1.2641052
	-3.5051589	1.5102755	0.2401/10
H	3.3962127	1.5064314	0.8896003
H	4.1032892	0.6179824	2.2355494
H	-4.1483865	2.0470824	0.7429684
С	4.4492254	-0.3301997	0.2948691
С	-3.7943299	0.7906650	-1.0001862
Η	4.8791985	0.3574948	-0.4665759
Η	5.3239074	-0.7326465	0.8472949
Η	-4.6963112	1.1331802	-1.5313117
С	3.7751285	-1.5277916	-0.3808831
Η	4.5459080	-2.0826029	-0.9567501
Η	3.4140359	-2.2277021	0.4025616
С	2.5917246	-1.2349607	-1.3433296
Η	2.8388138	-1.5464091	-2.3767034
Η	1.6930094	-1.8038449	-1.0432127
С	-2.9624434	-0.2198044	-1.5572985
Ν	2.1438908	0.1884366	-1.4659151
С	-1.7963749	-0.6319175	-0.8054458
С	1.3125269	0.7604192	-0.5242613
Č	-3.2700949	-0.8677032	-2.7854421
C	2.5287944	0.8830942	-2.5747108
н	-4 1521397	-0 5396891	-3 3589898
н	3 2003041	0 3537495	-3 2678320
C	-2 4887060	-1 9251136	-3 2328711
c	2.4007000	2 1780584	-2 8227112
с ц	2.0051445	2.1700504	-2.0227112 A 1747435
и П	-2.7437550	2 7010030	2 7 9 2 9 2 1
	2.4201303	2.1019039	-3.1203031
	-1.3031404	-2.3023334	-2.4000341
	1.2016808	2.1/38301	-1.9092107
H	-0.8182681	-3.2038247	-2.7965380
H	0.8270253	3.7969888	-2.0762056
C	-1.0397795	-1.7472531	-1.2757702
C	0.8261507	2.0568852	-0./654803
Η	-0.2269214	-2.1431303	-0.6487008
Н	0.1794281	2.5197666	-0.0048530



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#### MIN-mpp-pp:

55			
E1	= -1151.1912	11574	
С	-0.0007815	0.0008537	-0.0010155
С	-0.0018205	0.0003977	1.4203582
Ċ	1 2318259	-0.0034945	2 0954014
c	1 31/8282	0.0031915	2.0551011
с u	-1.3140202	0.0720815	2.1039402
п	1.2450555	-0.0037893	5.19/8515
H	-1.1595901	-0.1435228	3.2458524
Н	-2.0050989	-0./1/1630	1.7952953
С	2.4384138	0.0062928	1.3891378
С	-1.9885006	1.4581504	2.0150323
Η	3.3914784	0.0201245	1.9432827
Η	-1.5208535	2.2043562	2.6944227
Η	-3.0575113	1.3850269	2.3101308
С	-1.8606831	2.0183443	0.5899326
Ĥ	-0.8206702	2 3485006	0 3885695
н	-2 5297054	2 8869481	0.4330855
C	2.5257054	0.0288648	0.120620
C N	2.4/10495	0.0288048	-0.0189029
N	-2.2035045	0.9914514	-0.431/081
C	1.2350173	0.0064572	-0.7249922
C	-1.3289024	-0.0263665	-0.6880889
С	3.7980448	0.0084318	-0.7411938
С	-3.4444977	1.0619770	-1.0300938
Η	3.7564701	0.6361515	-1.6578602
Η	4.5812053	0.4647587	-0.1005398
Η	-4.0644264	1.9263139	-0.7499064
С	4.2146889	-1.4426235	-1.0995856
С	-3.8626971	0.1030599	-1.9230505
Ĥ	5.0304824	-1.4161031	-1.8563654
н	4 6460185	-1 9301747	-0 1989839
ц	4 8520868	0.2003050	2 39/7750
C	3 051/230	0.2003730	1 5817301
	2 429 4927	-2.3100342	-1.3617301
п	3.4284837	-3.3400301	-1.//089//
Н	2.2933669	-2.428/420	-0.///401/
C	2.3920143	-1.9238081	-2.9021278
Η	3.1191886	-2.0844970	-3.7225156
Η	1.5189771	-2.5825180	-3.1050277
С	-3.0380920	-1.0250794	-2.1921881
Ν	1.8794189	-0.5145468	-3.1317122
С	-1.7504167	-1.1003210	-1.5355246
С	1.2473215	0.2788788	-2.1953836
С	-3.4606428	-2.0901468	-3.0354436
С	1.9701816	-0.1007329	-4.4341146
Н	-4.4379713	-2.0198605	-3.5392482
Н	2 4934956	-0 7854058	-5 1180994
C	-2 6642883	-3 2175420	-3 1909407
c	1 /336078	1 007/188	4 8861050
с u	2 0050622	1.0974100	2 9 2 7 9 7 1 4
11 11	-5.0059025	-4.0494302	-3.02/0/14
П	1.3312/08	1.5755017	-3.9448/4/
C	-1.424/130	-3.3230754	-2.4999420
C	0.7662838	1.9188448	-3.9655144
H	-0.8352290	-4.2504216	-2.5872207
Η	0.3372313	2.8856364	-4.2755183
С	-0.9699202	-2.2864636	-1.6957514
С	0.6880332	1.4976517	-2.6347142
Η	-0.0345592	-2.3938529	-1.1267963
Η	0.2283841	2.1487694	-1.8768029



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#### **TS-mmp-pp:**

55			
E1	= -1151.1528	86667	
С	0.0001625	-0.0029193	-0.0006383
С	-0.0001583	-0.0032388	1.4166000
С	1.2388147	0.0017229	2.0812198
C	-1.2910026	-0.0340195	2.2112896
H	1.2752359	0.0610456	3.1813744
н	-1.0679034	-0 2005419	3 2848344
н	-1 9010601	-0.9092207	1 8918060
C	2 4060072	0.2135860	1.3565/01
C	2.4000072	1 2561027	2 0545591
С	-2.1240000	0.2721721	2.0343361
Н	3.3402474	-0.3/31/21	1.9102700
н	-1.7022988	2.0838354	2.005/394
Н	-3.1556692	1.07/1396	2.42/3044
C	-2.1522223	1.7338132	0.5969439
Н	-1.1828459	2.2019216	0.3229371
Η	-2.9510403	2.4802107	0.4198014
С	2.4507671	-0.2982287	-0.0548315
Ν	-2.3743411	0.5945662	-0.3313603
С	1.2425068	0.0270603	-0.7766277
С	-1.3431112	-0.2543616	-0.6231384
С	3.7617042	-0.8947609	-0.5689221
С	-3.6500028	0.4048383	-0.8219589
Н	4.5183880	-0.1137569	-0.8132083
Н	4 2026193	-1 4107885	0 3081865
н	-4 3957881	1 1547669	-0.5209016
$\hat{\mathbf{C}}$	3 6279683	-1 9172395	-1 71/90/7
C	3 0/00572	0.6620604	1 63/5/5/
с u	-3.9490372	-0.0020004	1 5300335
п	4.5241709	-2.7041462	-1.3390333
п	2.0078038	-2.3043792	-1./050595
Н	-4.9744320	-0.7764163	-2.019/618
U U	3.9358823	-1.29/3651	-3.0801259
Н	5.0388840	-1.2112766	-3.2092676
H	3.5797417	-1.9361205	-3.9186395
С	3.4021580	0.1159166	-3.2165719
Η	3.7275832	0.7694966	-2.3843672
Η	3.7906075	0.5909412	-4.1381560
С	-2.9479394	-1.6275912	-1.9374728
Ν	1.9097156	0.2673640	-3.2948551
С	-1.6178248	-1.4305902	-1.3990850
С	1.0755894	0.4868420	-2.1968551
С	-3.2317887	-2.7839050	-2.7143970
С	1.4570544	0.4540063	-4.5711448
Н	-4.2463348	-2.9178217	-3.1227269
Н	2.1755418	0.1942345	-5.3639080
C	-2.2486613	-3 7406284	-2.9312631
c	0.2271562	1 0207191	-4 8740212
н	-2 /778058	-1 6/207171	-3 5209266
и П	-2.4778058	1 1/68720	5.0240803
n C	-0.0771403	2 5757692	-3.3240803
C	-0.75555454	-5.5757065	2 70070019
U U	-0.300401/	1.34/1033	-5.798/551
H	-0.1966422	-4.3638958	-2.5124/81
H	-1.3916315	2.1729172	-3.9683344
C	-0.6394990	-2.4475583	-1.6231015
С	-0.0667910	1.2798313	-2.4983646
Η	0.3571095	-2.3537978	-1.1688507
Η	-0.6034159	1.7455411	-1.6667513



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#### MIN-mmp-pp:

55			
E1	= -1151.1900	20642	
С	-0.0018086	0.0028035	0.0000678
С	-0.0008595	0.0046703	1.4200521
С	1.2347086	0.0029897	2.0875141
C	-1.3180227	0.1008085	2.1597045
Ĥ	1.2583773	-0.0178687	3.1895804
Н	-1 1638211	-0.0539156	3 2473656
н	-2.0007333	-0.7151563	1 8309715
C	2 4316427	0.0346910	1 3680649
c	-2.0064316	1 4721587	1 9338215
ч	3 3867220	0.0161402	1.0184427
н	-1 5339726	2 2572/3/	2 56/355/
ц	3 0681210	1 /038088	2.30+333+
II C	-3.0081210	1.4038088	2.2333373
с u	-1.9230380	1.9003900	0.4706074
п	-0.9018/79	2.5212626	0.2329081
П	-2.6280044	2.8008048	0.2906064
	2.4655202	0.1381947	-0.0405132
N	-2.2495964	0.8694/62	-0.4/20569
C	1.2223164	0.1299975	-0./3/2024
C	-1.3494978	-0.1415532	-0.6398147
C	3.8419278	0.2041491	-0.6923794
С	-3.5129457	0.8264414	-1.0228355
Η	4.5600441	0.4779912	0.1096145
Η	4.1318136	-0.8317078	-0.9900268
Η	-4.1502809	1.7026149	-0.8339320
С	4.0949405	1.1292527	-1.8994771
С	-3.9318824	-0.2600865	-1.7564577
Η	5.1963989	1.1817018	-2.0379006
Η	3.7254188	0.6643905	-2.8413445
Η	-4.9404591	-0.2555840	-2.1986068
С	3.5696963	2.5685446	-1.7918172
Η	3.9728581	3.0745839	-0.8862564
Η	3.9464614	3.1473526	-2.6639904
С	2.0279513	2.6944277	-1.7434502
Н	1.6247375	2.5182195	-0.7285197
Н	1.6933887	3.6970182	-2.0771403
С	-3.0902106	-1.4009918	-1.8822297
Ν	1.4112544	1.6911284	-2.6532241
С	-1.7739990	-1.3466070	-1.2803799
Ċ	1.1621433	0.4043053	-2.2115269
C	-3.5185515	-2.5968936	-2.5227801
Ĉ	1.3078966	2.0256301	-3.9698672
H	-4.5149701	-2.6272888	-2.9921269
Н	1 5389677	3 0727160	-4 2199474
C	-2 7020657	-3 7207829	-2 5209652
C	0.9552429	1 0010733	1 0370765
н	-3 0/693//	-4 6515265	-7.9999798
ц	0 8800728	1 4027015	5 0012078
п С	1 4346344	3 6025362	1 872/756
C	0 7268612	-0.2252160	-1 5361297
с и	0.7300043	4 6007471	1 82/0515
п U	-0.0249031	-4.009/4/1	-1.0347313
п	0.4989/40	-1.014454/	-3.2/88344
C	-0.9/14800	-2.3304132	-1.2/12990
	0.0040072	-0.50351/2	-3.1/03809
H	-0.0040073	-2.5259906	-0./452180
Н	0.6825190	-1.3997/66	-2.8481015



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#### TS-mmm-pp:

55			
E1	= -1151.1857	70944	
С	0.0278105	-0.0375594	0.0066372
С	0.0078674	-0.0539692	1.4286441
С	1.2302012	-0.0445766	2.1233872
С	-1.3256141	-0.0111741	2.1438087
Ĥ	1.2246205	-0.0804940	3.2253314
н	-1 1892200	-0 1844495	3 2309798
н	-1 9743399	-0.8417029	1 7834610
C	2 1/88552	0.0054530	1.7054010
C	2.4400332	1 3404478	1.9317036
С	-2.0334373	1.3404478	2.0017202
п	3.3943067	-0.0399797	2.0017503
п	-1.02/01/0	2.1201903	2.3928010
П	-3.1220376	1.2281078	2.2231005
C	-1.9517232	1.8/33606	0.4908388
Н	-0.9342137	2.2620859	0.2826690
Н	-2.6723055	2.6946648	0.3096411
С	2.4951043	0.1004505	0.0322398
Ν	-2.2236724	0.7987617	-0.5001788
С	1.2671769	0.1012903	-0.6901691
С	-1.2948478	-0.1843247	-0.6786284
С	3.8191124	0.1937456	-0.6989278
С	-3.4627298	0.7552335	-1.1032968
Η	4.5787473	-0.3568138	-0.1050177
Η	3.7365481	-0.3722343	-1.6512238
Н	-4.1271784	1.6075270	-0.8995321
С	4.3851814	1.6192179	-1.0030285
С	-3.8261381	-0.3017143	-1.9063628
Н	5.1914517	1.8505049	-0.2758030
Н	4.9002980	1.5613877	-1.9863031
Н	-4.8160035	-0.2963856	-2.3889522
C	3.4467225	2.8500147	-0.9981601
н	3 3627742	3 2575667	0.0331770
н	3 9470808	3 6484817	-1 5870634
C	1 9845717	2 7118782	-1 4869296
ч	1.2055065	2.7110702	0.6408304
п п	1.5055905	2.4072038	1 0258404
П С	2 0510708	1 4146435	2 0570076
U N	-2.9319708	-1.4140433	-2.0370070
IN C	1.7343340	1.0048499	-2.3233078
C	-1.0030830	-1.3030441	-1.3981874
C	1.3021289	0.3893980	-2.15/4492
C	-3.3241457	-2.5832509	-2.111/853
C	1.9629003	2.0018196	-3.8266026
Н	-4.2991212	-2.6098906	-3.2903820
Η	2.2768704	3.0410246	-4.0125773
С	-2.4817519	-3.6875652	-2.8003142
С	1.7859889	1.0820119	-4.8551806
Η	-2.7840146	-4.5984903	-3.3420469
Η	1.9681367	1.3909489	-5.8961915
С	-1.2443201	-3.6670226	-2.0962053
С	1.3839312	-0.2208860	-4.5252801
Η	-0.6161551	-4.5723107	-2.0788641
Н	1.2467967	-0.9806882	-5.3120457
С	-0.8341651	-2.5286900	-1.4158301
С	1.1748423	-0.5546791	-3.1789564
Н	0.1084384	-2.5330306	-0.8465494
Η	0.8881468	-1.5785683	-2.9026283



# MIN-saddlequat-mpm-pp (corresponds to the isolated species $[S_{\omega}R_a-4]$ ):

55			
<b>E</b> 1	= -1151.1953	60386	
C	-0.0005521	0.0012307	0.0008214
С	0.0001168	0.0006170	1.4206804
С	1.2344496	-0.0008721	2.0948302
$\tilde{c}$	-1 3207701	0.0858059	2 1550733
н	1.2/98037	-0.038/1831	3 1966311
и П	1.1714020	0.0604242	2 2422141
п	-1.1/14030	-0.0094342	3.2433141
п	-1.9902975	-0./541905	1.8214307
C	2.4365605	0.0453656	1.3839900
C	-2.01/9366	1.4529174	1.9277251
H	3.3918295	0.0227426	1.9342663
H	-1.5557353	2.2395757	2.5639233
Η	-3.0810742	1.3754466	2.2422968
C	-1.9302438	1.9547374	0.4733587
H	-0.9092614	2.3166313	0.2366112
Н	-2.6380135	2.7863996	0.2885770
С	2.4625766	0.1653609	-0.0219076
N	-2.2455182	0.8624308	-0.4847038
C	1 2268165	0 1448092	-0.7235360
$\tilde{c}$	-1 3426597	-0.1469213	-0.6480917
$\frac{c}{c}$	3 7998072	0.3811333	-0.7046860
$\frac{c}{c}$	-3 5006888	0.8231060	-1.0538463
н	4 5579000	-0.2328836	-0.1732594
U U	3 7028556	0.0005753	1.7520021
и П	1 1 4 0 8 0 5 3	1.6078534	0.8681636
	4.1406933	1.0970334	-0.8081030
	4.2373797	0.2570200	-0.0307034
	-3.9083333	-0.2579290	-1.8019762
H	4.1119054	2.2350881	0.38/0200
H	5.3528324	1.9021409	-0.8340880
H	-4.9099034	-0.2497892	-2.259/616
C	3.5837574	2.8193149	-1.6435264
Н	3.8204462	3.8640246	-1.3440446
Н	4.0232075	2.6989128	-2.6612560
С	2.0504817	2.7334898	-1.7751366
H	1.5499569	2.5969578	-0.7963798
H	1.6526294	3.6601496	-2.2351374
C	-3.0656196	-1.3986176	-1.9218205
N	1.6207907	1.6167274	-2.6756214
C	-1.7587929	-1.3486738	-1.2995106
C	1.2539588	0.3724610	-2.2016379
C	-3.4851561	-2.5911408	-2.5744486
C	1.6903172	1.8711426	-4.0147525
H	-4.4736273	-2.6178925	-3.0605288
Н	1.9905373	2.8923175	-4.2959940
С	-2.6711015	-3.7166829	-2.5627620
С	1.4082035	0.8983010	-4.9662135
Н	-3.0096952	-4.6449313	-3.0509985
Н	1.4790608	1.1497729	-6.0358185
C	-1.4155337	-3.6940465	-1.8913180
C	1.0564958	-0.3853535	-4.5230486
н	-0.8097702	-4 6134298	-1 8444434
н	0.855/699	-1 19/032/	-5 2445969
$\frac{1}{C}$	-0.9596630	-2 53/6880	-1 2792625
C	0.9590039	0.6322576	3 1/60127
Ч	0.0020665	2 5250220	0.7226425
	0.7310275	1 6375402	2 7812025
п	0.7519275	-1.05/3492	-2.7012923



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#### **TS-mpm-pp:**

55			
E1	= -1151.1499	54534	
С	0.5505574	-1.1349541	0.2202276
С	0.9712612	-2.4265957	0.7183714
С	0.0299759	-3.4622705	0.8633451
C	2.3844919	-2.7636986	1.1563394
H	0.3796205	-4.4508813	1.2037336
Н	2 3405773	-3 5930998	1 8921661
н	2.8276923	-1 8949989	1 6905822
C	-1 3213654	-3 2620768	0.6190617
c	3 2879383	-3 1379396	-0.0271463
н	-2 0276784	-4 1027102	0.7150/95
н	3 0709616	-4.1027102	-0./137833
н	4 3560304	3 12/81/8	0.276/010
II C	4.3309304	-3.1240140	1 1109192
С Ц	2.9049021	-2.1210307	-1.1190103
п	2.0208070	-2.3316201	-1.0237270
П	3.7723302	-2.0629444	-1.8993974
C N	-1.8190748	-1.9589853	0.3982022
N	2.8536264	-0.7463272	-0.5483304
C	-0.8914460	-0.8894745	0.2382975
C	1.627/686	-0.1881411	-0.2205612
C	-3.3350602	-1.8121611	0.414/032
С	4.0428865	-0.0624504	-0.4206320
Н	-3.7383696	-2.6686465	0.9927038
Η	-3.6612482	-0.9088892	0.9764278
Η	4.9496814	-0.6403972	-0.6533288
С	-3.9796941	-1.8384635	-0.9962676
С	4.0772711	1.2508380	-0.0239743
Η	-3.4334792	-2.5742380	-1.6284130
Η	-5.0151607	-2.2304165	-0.9051940
Η	5.0413574	1.7511832	0.1542625
С	-4.0526064	-0.4850098	-1.7114616
Η	-4.3275966	-0.6451020	-2.7770948
Η	-4.8711159	0.1386843	-1.2827805
С	-2.7595748	0.3404283	-1.7056199
Н	-1.8787537	-0.2736215	-1.9831130
Н	-2.8327073	1.1829939	-2.4239924
С	2.8572383	1.9803785	-0.0289852
Ν	-2.4695510	0.9568181	-0.3731964
С	1.6207044	1.2686014	-0.2885893
Ċ	-1.5170459	0.4441594	0.4739507
C	2.8599866	3.4017250	0.0648394
C	-3.1758960	2.0792711	-0.0443420
Ĥ	3.8048405	3.9127830	0.3103100
Н	-3 9143341	2.4183452	-0 7873913
C	1 7204755	4 1307604	-0 2426749
c	-2 9741082	2 7440582	1 1584981
н	1 7362911	5 2317182	-0.2053915
н	-3 5739566	3 6380089	1 3893512
C	0 5671202	3 1178877	0.7064090
C	-2 0050/1292	2.77,00// 2.7/81279	2 0/80704
с и	-2.0030400 0.2020252	4.0264720	2.0+07/00 1 102/100
п U	-0.2020230	4.0204/29	-1.1034108
П	-1.823/029	2.7440041 2.0576255	3.0109324
C	0.3134849	2.03/0233	-0.7078387
U U	-1.280/283	1.1001034	1.0943601
H	-0.3451384	1.5645083	-1.1/14204
н	-0.3322369	0.0780362	2.3181933



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#### MIN-mpm-pp:

55			
E1	= -1151.1501	97842	
С	0.7609798	-1.1034779	0.0719070
С	1.3608080	-2.3798036	0.4012301
С	0.5658178	-3.5402982	0.3700395
С	2.7769901	-2.5543864	0.9206990
Ĥ	1.0462334	-4.5161773	0.5508951
Н	2.8207740	-3 4958071	1 5068033
н	2.9886350	-1 7295735	1 6374965
C	-0.8101782	-3 4798793	0 1916919
c	3 8640606	2 5467627	0.1510515
ч	1 4006575	4 4108234	0 1752846
и П	3 0101265	3 5080540	0.1752840
и П	<i>A</i> 8641187	-3.3089349	0.2066567
n C	4.0041107	-2.3651540	1 1 2 1 6 9 2 4
	3.40/4090	-1.4412279	-1.1310624
п	4.22992231	-1.7000397	-1./9521/4
П	4.5288508	-1.1220429	-1./802820
C	-1.4/92219	-2.2335289	0.2195094
N	3.0051150	-0.2080119	-0.4331824
C	-0./010888	-1.0443421	0.1622298
C	1.6521423	0.0418060	-0.2402238
C	-2.9894262	-2.2947772	0.4095082
С	3.9686640	0.7353715	-0.1534119
Н	-3.2116788	-3.2568119	0.9152518
Η	-3.3452194	-1.5111876	1.1144879
Η	5.0098966	0.3968047	-0.2688901
С	-3.8042050	-2.2464513	-0.9084335
С	3.6388889	2.0159510	0.2210121
Η	-3.2679414	-2.8330625	-1.6879266
Η	-4.7705627	-2.7706989	-0.7483568
Η	4.4259573	2.7277145	0.5130493
С	-4.1083079	-0.8389487	-1.4287654
Η	-4.4948628	-0.9037251	-2.4694414
Η	-4.9255293	-0.3687023	-0.8344404
С	-2.9096775	0.1177869	-1.4578426
Н	-2.0121979	-0.3754963	-1.8833596
Н	-3.1383594	1.0100813	-2.0767312
С	2.2944776	2.4395227	0.0225164
Ν	-2.5362217	0.6411972	-0.1058687
С	1.3078067	1.4500898	-0.3550159
Ċ	-1.4396447	0.1816303	0.5849176
Ĉ	1.9425946	3.8197926	0.0389407
C	-3 3135853	1 6472125	0 3943892
н	2 6927194	4 5549309	0.3724557
н	-4 1672706	1.9520814	-0.2310862
C	0.7128370	1.9320014	-0.4506014
C	3 0414505	2 2462818	1 6160441
н	0.4617083	5 310/3/7	0.4757776
и П	3 7001560	3.0477071	1 0857082
П С	-3.7001309	3.0477071	1.9657062
C	1 025/007	J.20J42J0	-1.01344/9
U U	-1.723470/	1.0030009	2.3490443
п	-1.0/80390	3.0338083	-1.343/492
Н	-1.0843544	2.24/8/33	3.3292644
C	0.1040/40	1.9248828	-0.94/0830
C	-1.1360/51	0.7766715	1.8258278
H	-0.5412861	1.2132086	-1.4755935
Н	-0.2747572	0.3866232	2.3888391



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#### TS-mpm-0p:

55			
E1	= -1151.1441	64944	
С	0.8742341	-1.1721358	-0.1026160
С	1.4479203	-2.5026901	-0.0802352
С	0.5924948	-3.5758103	-0.4236176
Ċ	2,7560320	-2.9637854	0 5505996
н	1 0346484	-4 5764081	-0 5614822
н	2 8000//2	4 0240075	0.2503730
и П	2.0999442	3 0003187	1 6302333
n C	2.3080329	-3.0093187	1.0392333
C	-0.7894178	-3.4408327	-0.4003993
U U	4.0765205	-2.1980/11	0.3/3530/
H	-1.4116514	-4.3342/91	-0.6649338
Н	4.8541786	-2.8698677	-0.0504060
Н	4.4784769	-1.8383985	1.3444959
С	3.9104585	-1.0400053	-0.5768195
Η	3.4572039	-1.3754221	-1.5343562
Η	4.8864705	-0.5750706	-0.8198711
С	-1.4046965	-2.2446800	-0.0372710
Ν	3.0500856	0.0669396	-0.0690493
С	-0.5851054	-1.0929344	0.0665012
С	1.6742464	0.0603849	-0.2326070
С	-2.8620954	-2.3457906	0.3944007
С	3.7164776	1.2028497	0.3400776
Н	-3.0076513	-3.3790842	0.7731085
Н	-3.0635054	-1.6871946	1.2686087
Н	4.7902452	1.0688769	0.5429718
C	-3.9087486	-2.0934184	-0.7166493
C	3 0937104	2.4237512	0 4371859
н	-3 5599173	-2 5677769	-1 6618621
н	-4 8505875	-2 6158420	-0.4442613
н	3 6471749	3 2963234	0.8162545
$\hat{C}$	_1 2272213	-0.6166573	-0.959/2/1/
с u	4 8058160	0.5110425	1 0020255
п п	4.8038100	0.2175461	-1.9029233
П	-4.00/9/09	-0.2173401	1 0802020
	-2.9912948	0.2651755	-1.0892929
н	-2.2114384	-0.2130405	-1.090/452
Н	-3.2505084	1.2434533	-1.5801151
C	1.8092794	2.5598490	-0.1623558
N	-2.3786385	0.6568205	0.2256554
C	1.1255314	1.3590820	-0.5870873
С	-1.2198338	0.0921493	0.7130471
С	1.2572745	3.8348400	-0.4709138
С	-3.0338224	1.6315459	0.9260650
Η	1.7709485	4.7397851	-0.1080798
Η	-3.9477571	2.0256825	0.4564961
С	0.1456863	3.9361395	-1.2973110
С	-2.5771249	2.0966138	2.1512237
Η	-0.2471071	4.9273387	-1.5760651
Η	-3.1451074	2.8770831	2.6805786
С	-0.4320243	2.7630473	-1.8511695
С	-1.3970858	1.5442883	2.6803297
Н	-1.2281689	2.8560826	-2.6085243
Н	-1.0121259	1.8728137	3.6594698
С	0.0267151	1.5037032	-1.4821572
Ċ	-0.7328009	0.5517102	1.9554555
H	-0.3875899	0.6053916	-1.9606676
H	0.1698000	0.0733217	2.3633756



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#### MIN-helquat-mpm-mm (corresponds to the isolated species [M-5]):

<mark>55</mark>			
E1	= -1151.200	<mark>561731</mark>	
C	0.000000	0.000000	<mark>0.000000</mark>
C	0.000000	0.000000	1.419895
C	1.235762	0.000000	2.092256
C	-1.311997	-0.073587	2.169188
Н	1.250506	0.015838	3.194550
H	-2.004092	0.716072	1.798671
H	-1.156638	0.138438	3.246913
C	2.439183	-0.052033	1.384825
C	-1.981329	-1.460927	2.008799
H	3.389949	-0.095066	1.941872
H	-3.049733	-1.392468	2.307176
H	-1.509432	-2.208897	2.683244
C	-1.855895	-2.013983	0.580065
H	-2.525453	-2.881649	0.420575
H	-0.817133	-2.343095	0.371775
C	2.474079	-0.103654	-0.025401
N	-2.203233	-0.980678	-0.433836
C	1.236434	-0.036178	-0.724475
C	-1.331448	0.041587	-0.683107
C	3.820920	-0.276347	-0.707013
C	-3.446297	-1.047892	-1.027729
H	4.462101	-0.869419	-0.021609
H	3.727429	-0.890402	-1.631220
H	-4.063183	-1.916405	-0.753875
C	4.552749	1.051171	-1.019337
C	-3.869776	-0.080754	<mark>-1.909391</mark>
H	4.452308	1.731588	-0.143619
H	5.639974	0.843005	-1.116756
Н	-4.861382	-0.175644	-2.378866
C	4.097100	1.772271	-2.292202
H	4.544533	2.790354	-2.309571
H	4.491846	1.258350	-3.199253
C	2.578311	1.953112	-2.451859
H	2.098757	2.203686	-1.485765
H	2.354827	2.770271	-3.166764
C	-3.048751	1.051798	-2.169819
N	1.891394	0.741515	-3.001521
C	-1.758859	1.123902	-1.516394
C	1.237191	-0.173025	-2.205965
C	-3.476050	2.123220	-3.002495
C	1.956956	0.574703	-4.355683
H	-4.455377	2.055745	-3.502786
H	2.502337	1.353875	-4.910179
C	-2.681270	3.252389	-3.152621
C	1.370446	-0.510385	-4.994718
H	-3.025992	4.088480	-3.782386
H	1.454687	-0.604263	-6.088472
C	-1.438878	3.353880	-2.466075
C	0.689018	-1.460796	-4.216384
H	-0.848738	4.280742	-2.550289
H	0.226199	-2.344161	-4.685746
C	-0.981642	2.312362	-1.670474
C	0.627135	-1.278331	-2.830449
H	-0.045541	2.418804	-1.103581
H	0.137125	-2.027761	-2.191418



# 6) Monitoring transformation (+)- $[S_a, R_a-4]$ [TfO]<sub>2</sub> $\rightarrow$ (-)-[P-5][TfO]<sub>2</sub> by chiral CE and NMR

# Kinetics of the conversion of enantiopure saddlequat (+)- $[S_a, R_a-4][TfO]_2$ into enantiopure helquat (-)- $[P-5][TfO]_2$ in DMSO- $d_6$ at 100 °C:

5.8 mg of optically pure saddlequat (+)-[ $S_a$ , $R_a$ -4][TfO]<sub>2</sub> was dissolved in 0.4 mL of dry DMSO- $d_6$ . This solution was transferred to an NMR tube. Two compartments of a block heater (Rotilabo<sup>©</sup> - block thermostat model H 250 purchased from Carl Roth GmbH) were filled with silicon oil and the heater was set to 100 °C (temperature checked by a digital electronic thermometer; thermometer was produced inhouse by the IOCB development workshops). The starting solution was analyzed by NMR and CE (sample for CE of ca 14 µL was taken using thin glass capillary used for making spots on TLC). Then the NMR tube was heated in the block heater to 100 °C and every 30 min, it was quickly cooled to room temperature and an <sup>1</sup>H NMR spectrum was recorded (600 MHz). A sample of ca 14 µL was taken each time for CE measurement and the composition was analyzed as described in the CE section (page ESI 25). See Scheme S3 for CE charts from the individual CE analyses. The experiment was stopped after 210 min of heating. Results from these NMR and CE analyses are summarized in Table S2.

t/min	x(saddle-CE)	x(saddle-NMR)	ln(x(saddle-CE))	ln(x(saddle-NMR))
0	1	1	0	0
30	0.81564	0.787402	-0.2037822	-0.2390169
60	0.66803	0.641026	-0.4034222	-0.44468582
90	0.53512	0.520833	-0.6252643	-0.65232519
120	0.429	0.420168	-0.8462984	-0.86710049
150	0.34793	0.333333	-1.055754	-1.09861229
180	0.27462	0.243902	-1.292367	-1.41098697
210	0.21448	0.185185	-1.5395388	-1.68639895

**Table S2** Dataset obtained from CE and NMR monitoring of  $(+)-[S_a,R_a-4][TfO]_2 \rightarrow (-)-[P-5][TfO]_2$  at 100 °C.

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Scheme S3 CE charts from the individual composition analyses during the transformation  $(+)-[S_a,R_a-4][TfO]_2\rightarrow(-)-[P-5][TfO]_2$ . See also Scheme 8 in the manuscript.

Conversion of the enantiopure saddlequat (+)- $[S_a, R_a-4]$ [TfO]<sub>2</sub> into enantiopure helquat (-)-[P-5][TfO]<sub>2</sub> can be described by first order kinetics:

$$x(t) = x_0 e^{-kt}$$

where  $x_0$  is the initial molar fraction of saddlequat, x(t) represents the molar fraction of saddlequat at time t. Using this equation, the rate constant of conversion k can be obtained from the measured data. From this constant, the half-life of the saddlequat can be calculated as  $T_{1/2} = (\ln 2)/k$ . By using transition state theory, the activation Gibbs energy of the conversion ( $\Delta G^{\neq}$ ), can be obtained from the constant k and this value can be directly compared with the barrier calculated by the DFT-D calculation (see section 5 of this ESI).

$$k = \frac{k_B T}{h} e^{-\frac{\Delta G^{\#}}{RT}}$$

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where  $k_B$  is the Boltzmann constant (1.3806504  $\cdot$  10<sup>-23</sup> J/K), *R* is the universal gas constant (8.314472 J/K/mol), *h* is Planck's constant (6.62606896  $\cdot$  10<sup>-34</sup> J·s) and *T* is thermodynamic temperature (in Kelvins).



**Figure S1** Plot of the data obtained from CE analysis. Values leading to construction of this plot are summarized in Table S2.



**Figure S2** Plot of the data obtained from NMR analysis. Values leading to construction of this plot are summarized in Table S2.

	k / min <sup>-1</sup>	$T_{1/2}/h$	$k/s^{-1}$	$\Delta G^{\neq} [kJ/mol]$
CE	$7.30 \cdot 10^{-3}$	1.6	$1.22 \cdot 10^{-4}$	120.1
NMR	$7.87 \cdot 10^{-3}$	1.5	$1.31 \cdot 10^{-4}$	119.8
Average	$7.59 \cdot 10^{-3}$	1.55	$1.27 \cdot 10^{-4}$	120.0

**Table S3** Summary of results obtained from CE and NMR measurements during the transformation  $(+)-[S_a,R_a-4][TfO]_2 \rightarrow (-)-[P-5][TfO]_2$  and the corresponding value of  $\Delta G^{\neq}$ .

The data obtained from CE and NMR measurements (Table S2) are plotted in Figure S1 and Figure S2, respectively. These plots lead to the results summarized in Table S3. The Gibbs activation energy value of ( $\Delta G^{\neq}$ ) 118.5 kJ/mol calculated using the described DFT-D methods, in DMSO at 100 °C (see section 5 of this ESI) is in good agreement with the values determined experimentally.

# 7) Monitoring transformation [rac-4][TfO]<sub>2</sub> $\rightarrow$ [rac-5][TfO]<sub>2</sub> by NMR

Conversion of racemic saddlequat [rac-4][TfO]<sub>2</sub> into racemic helquat [rac-5][TfO]<sub>2</sub> in DMSO- $d_6$  at 100 °C was performed according to the following protocol:

5 mg of saddlequat [rac-4][TfO]<sub>2</sub> was dissolved in 0.4 mL of dry DMSO-*d*<sub>6</sub>. This solution was transferred to an NMR tube. Two compartments of a block heater (Rotilabo<sup>©</sup> - block thermostat model H 250 purchased from Carl Roth GmbH) were filled with silicon oil and the heater was set to 100 °C (temperature checked by a digital electronic thermometer). The starting solution was analyzed by <sup>1</sup>H NMR. Then the NMR tube was heated in the block heater to 100 °C and every 30 min, it was quickly cooled to room temperature and a <sup>1</sup>H NMR was recorded (600 MHz). Following this procedure, a set of seven datapoints were accumulated (0 min, 30 min, 60 min, 90 min, 120 min, 150 min, 180 min, 210 min). Results from this NMR experiment corresponded to the dataset in Table S2. Analysis of this dataset led to the activation Gibbs energy value of 120.1 kJ/mol as detailed in section 6 of this ESI (see summary Table S3). See Scheme 5 in the manuscript for the relevant NMR spectra.

# 8) ECD, UV-vis, FDCD, and fluorescence spectra of (+)-[ $S_a$ , $R_a$ -4][TfO]<sub>2</sub> and (-)-[P-5][TfO]<sub>2</sub>

ECD and UV-vis absorption spectra (Scheme 9 in the manuscript and Scheme S4) were measured using a J-810 spectropolarimeter (Jasco, Japan) equipped with a thermostat controlled cell holder attached to a Jasco Peltier temperature control system PTC-423S with an accuracy of ±0.2°C. ECD measurements were carried out at 25 °C and 100 °C in a quartz cuvette with an optical pathlength of 1 cm (Starna, USA). The conditions of measurement were as follows: scanning speed of 100 nm min<sup>-1</sup>, response time of 1 s, bandwidth of 0.5 nm and sensitivity of 1000 mdeg. The final spectrum was obtained as an average of 3 accumulations. The spectrum of the solvent was used as the baseline, and subtracted from the experimental spectra. The same device equipped with fluorescence accessories was used for fluorescence (Scheme S7) and fluorescence detected circular dichroism<sup>22</sup> (FDCD, Scheme S6 bottom) measurements with band width of 0.5 nm and 5 accumulations. The fluorescence was excited at 366 nm. In the fluorescence spectra the spectral region, which is not influenced by reabsorption, is shown (Scheme S7). The emission in FDCD was detected through a lowcut filter (420 nm). DMSO and MeOH solutions at a concentration of 2.10<sup>-4</sup> mol L<sup>-1</sup> were used for the measurement at 25 °C, the dimethylsulfoxide solution was used to follow the stereotransformation (+)- $[S_a, R_a-4]$ [TfO]<sub>2</sub> $\rightarrow$ (-)-[P-5][TfO]<sub>2</sub> at 100°C (see Scheme 9 in the manuscript). FDCD was run at the same concentration in methanolic solutions because strong quenching was observed in the DMSO solution.

The stereoforms (+)-[ $S_a$ , $R_a$ -4][TfO]<sub>2</sub> and (-)-[P-5][TfO]<sub>2</sub> are poorly resolved in their fluorescence spectra (Scheme S7), but clearly resolved in their ECD spectra in both DMSO and methanol (Schemes S4 and S5) as well as in FDCD spectra in methanol (Scheme S6 bottom).



Scheme S4 ECD ( $\Delta \epsilon$ ) and UV-vis absorption ( $\epsilon$ ) spectra of (+)-[ $S_a$ , $R_a$ -4][TfO]<sub>2</sub> (blue) and (-)-[P-5][TfO]<sub>2</sub> (black) in DMSO.



Scheme S5 Expanded version of Scheme S4 comparing experimental ECD ( $\Delta\epsilon$ ) and UV-vis absorption ( $\epsilon$ ) spectra of (+)-[ $S_a$ , $R_a$ -4][TfO]<sub>2</sub> (blue) and (-)-[P-5][TfO]<sub>2</sub> (black) measured in DMSO (full lines) with those measured in MeOH (dashed lines).



Scheme S6 ECD ( $\Delta \epsilon$ ) and FDCD spectra of (+)-[ $S_a$ , $R_a$ -4][TfO]<sub>2</sub> (blue) and (-)-[P-5][TfO]<sub>2</sub> (black) in DMSO (full lines) and in MeOH (dashed lines).

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Scheme S7 Fluorescence spectra of (+)- $[S_a, R_a-4]$ [TfO]<sub>2</sub> (blue) and (-)-[P-5][TfO]<sub>2</sub> (black) in MeOH,  $\lambda_{exc} = 366$  nm.

### 9) Racemization study with helquat (-)-[P-5][TfO]<sub>2</sub>

#### Kinetics of the racemization of helquat (-)-[P-5][TfO]<sub>2</sub> in DMSO-d<sub>6</sub> at 180°C:

The racemization study was performed with the sample of enantiopure helquat (-)-[*P*-**5**][TfO]<sub>2</sub>, that was prepared by transformation (+)-[ $S_a$ , $R_a$ -**4**][TfO]<sub>2</sub> $\rightarrow$ (-)-[*P*-**5**][TfO]<sub>2</sub> using the *optimized preparative procedure* (120 °C, 3 h) described in section 3 of the ESI. A block heater was set to 180 °C and allowed to reach thermal equilibrium. The NMR tube with the sample of (-)-[*P*-**5**][TfO]<sub>2</sub> (4 mg) in dry DMSO- $d_6$  (280 µL) was heated in the block heater to 180 °C. Every 30 min, a sample (ca 14 µL) for CE measurement was taken by a thin capillary. Enantiocomposition was analyzed as described in section 4 of the ESI. Electropherograms from the individual CE measurements are shown in Scheme S8. The experiment was stopped after 270 min of heating. Results of CE analysis performed during the measurement are summarized in Table S4 and plotted in Figure S3.



Scheme S8 CE electropherograms from the individual enantiocomposition analyses performed during the racemization of  $(-)-[P-5][TfO]_2$  at 180 °C in DMSO- $d_6$ .

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t/min	%P	%M	ee(P)	ln(ee(P))
0	98.12 %	1.88 %	96.24 %	-0.03833
30	95.64 %	4.36 %	91.28 %	-0.09124
60	91.83 %	8.17 %	83.66 %	-0.17841
90	88.61 %	11.39 %	77.22 %	-0.25851
120	85.78 %	14.22 %	71.56 %	-0.33463
150	83.67 %	16.33 %	67.34 %	-0.39542
180	81.36 %	18.64 %	62.72 %	-0.46649
210	79.34 %	20.66 %	58.68 %	-0.53307
240	77.96 %	22.04 %	55.92 %	-0.58125
270	74.78 %	25.22 %	49.56 %	-0.70199

**Table S4** Dataset obtained from CE measurements of samples taken in the course of the racemization of (-)-[*P*-**5**][TfO]<sub>2</sub> at 180 °C in DMSO- $d_6$ .

Racemization is a combination of two elementary processes: the P enantiomer converts to the M enantiomer with a rate constant k and the M enantiomer converts to the P enantiomer with the same rate constant k. When these two processes are combined, it is found that enantiomeric excess (*ee*) of one enantiomer decays *via* first order kinetics with a rate constant 2k:

$$ee = ee_0 e^{-2kt}$$

where  $ee_0$  is the initial enantiomeric excess of one enantiomer, 2k is the rate constant of racemization and t is time (ref. 6).

From the CE measurements, the content of *M*-helquat in the sample as a percent of total helquat composition (%*M*) at a given time can be determined. From this value, the enantiomeric excess of *P*-helquat ( $ee_P$ ) was calculated according to the formula:

$$ee_{P} = 100 - 2 \cdot \% M$$

ee<sub>P</sub> values follow first order kinetics:

$$ee_P = ee_{P0} \cdot e^{-2kt}$$

where  $ee_{P0}$  is the initial enantiomeric excess of *P*-helquat (in our case 98 %). From the measured dataset, the rate constant of racemization 2k was determined. Subsequently, racemization half-life was calculated as  $T_{1/2} = (\ln 2)/2k$ . Transition state theory is applied to transform the rate constant *k* to a value for Gibbs

activation energy, which can be directly compared with the barrier, obtained by DFT-D calculation (section 5 of this ESI). This is the barrier of interconversion of one enantiomer into the other.

$$k = \frac{k_B T}{h} e^{-\frac{\Delta G^*}{RT}}$$

where  $k_B$  is the Boltzmann constant (1.3806504  $\cdot$  10<sup>-23</sup> J/K), *R* is the universal gas constant (8.314472 J/K/mol), *h* is Planck's constant (6.62606896  $\cdot$  10<sup>-34</sup> J·s) and *T* is thermodynamic temperature (in Kelvins).



**Figure S3** Plot of the data obtained from CE analysis of samples taken in the course of the racemization of  $(-)-[P-5][TfO]_2$  at 180 °C in DMSO-*d*<sub>6</sub>. The values necessary to construct this plot are in Table S4.

	2k / min <sup>-1</sup>	$T_{1/2}/h$	k/min <sup>-1</sup>	$k/s^{-1}$	$\Delta G^{\neq} [kJ/mol]$
CE	$2.40 \cdot 10^{-3}$	4.8	$1.20 \cdot 10^{-3}$	$2 \cdot 10^{-5}$	153.3

**Table S5** Summary of results obtained from CE analysis of samples taken in the course of the racemization of (-)-[*P*-**5**][TfO]<sub>2</sub> at 180 °C in DMSO- $d_6$  and the corresponding value of  $\Delta G^{\neq}$  obtained from this dataset.

The data obtained from CE measurements (Table S4) are plotted in Figure S3. This plot leads to the results summarized in Table S5. The Gibbs activation energy value of ( $\Delta G^{\neq}$ ) 157.7 kJ/mol calculated

using DFT-D method described above (DMSO, 180 °C) is in agreement with the value 153.3 kJ/mol determined experimentally (Table S5).

### 10) X-ray analysis

Single-crystal X-ray diffraction data for  $[rac-2][PF_6]_2$ ,  $[rac-5][TfO]_2$ , and  $[P-5][ClO_4]_2$  were obtained from Nonius KappaCCD diffractometer by monochromatized MoK $\alpha$  radiation ( $\lambda = 0.71073$  Å) at 150(2)K. The structures were solved by direct methods (SIR92, Altomare, 1994) and refined by fullmatrix least squares based on  $F_2$  (SHELXL97). The hydrogen atoms were fixed into idealized positions (riding model) and assigned temperature factors  $H_{iso}(H) = 1.2 U_{eq}$ (pivot atom).

X-ray data for  $[S_a, R_a-4][(R, R)$ -dibenzoyl tartrate]<sub>2</sub> were measured on a Bruker-Nonius FR 591 with MoK $\alpha$  radiation, T = 100 (2) K;  $\theta_{max} = 25.55^{\circ}$ ; 7636 diffractions collected, 4149 independent ( $R_{int}$  =0.1296); Absorption correction type: empirical. Refinement method: full-matrix least-squares based on  $F^2$ , 735 parameters, goodness of fit 0.998, final R indices  $R[I > 2\sigma(I)] = 0.0649$ ,  $wR(F^2) = 0.1185$ , maximal/minimal residual electron density 0.53/-0.30 e Å<sup>-3</sup>.



# Preparation of X-ray quality crystals of the racemic helquat [*rac*-2][PF<sub>6</sub>]<sub>2</sub> starting from [*rac*-2][TfO]<sub>2</sub>

*Preparation of ion-exchange resin in*  $PF_6^-$  *cycle:* A column was prepared with a 3 mL bed volume of anion exchange resin in Cl<sup>-</sup> cycle (as purchased). 50 mL of a 0.5M aq. solution of NH<sub>4</sub>PF<sub>6</sub> was passed through the column to effect quantitative exchange of chloride anions for PF<sub>6</sub><sup>-</sup> anions. The absence of chloride anions in the eluent was confirmed by a lack of precipitate formation upon the combination of the eluent with a 0.1M aq. solution of AgNO<sub>3</sub>. The resin was then washed with water to remove all NH<sub>4</sub>PF<sub>6</sub>.

*Ion exchange:* Water was expelled from the column with a slight overpressure of air and MeOH was added to fill the void left by water. A solution of [rac-2][TfO]<sub>2</sub> (14.9 mg, 22 µmol) in 10 mL of MeOH was slowly run through the resin followed by 10 mL of pure MeOH to wash the resin. The solution that eluted from the column was then concentrated to dryness to obtain 13.3 mg of [rac-2][PF<sub>6</sub>]<sub>2</sub> as a yellowish powder. This powder was then used for preparation of X-ray quality crystals. The method of choice was slow diffusion. Crystals of sufficient quality were prepared *via* slow diffusion (ca. 7 days, RT) of *t*-BuOMe into a methanolic solution of the helquat [rac-2][PF<sub>6</sub>]<sub>2</sub>.

Crystal data for [*rac*-2][PF<sub>6</sub>]<sub>2</sub>: C<sub>27</sub>H<sub>26</sub>N<sub>2</sub>·2(F<sub>6</sub>P), M = 668.44, m.p. 250-252 °C; Triclinic, space group *P*-1 (No 2), a = 13.8836 (7) Å, b = 17.9623 (10) Å, c = 18.7911 (10) Å,  $\alpha = 75.440$  (2),  $\beta = 88.260$  (2),  $\gamma = 85.425$  (2)°; Z = 6,  $D_x = 1.473$  Mg m<sup>-3</sup>;  $\mu$ (Mo-K<sub> $\alpha$ </sub>) = 0.24 mm<sup>-1</sup>. dimensions of colorless crystal 0.30 × 0.28 × 0.25mm; X-ray data were measured on a Bruker APEX-II CCD with Mo  $K_{\alpha}$  radiation, T = 150 (2) K;  $\theta_{max} = 26.0^{\circ}$ ; 56115 diffractions collected, 17715 independent ( $R_{int} = 0.049$ ); Absorption correction type: none. Refinement method: full-matrix least-squares based on  $F^2$ , 1162 parameters, goodness of fit 0.71, final R indices R [ $I > 2\sigma(I)$ ] = 0.073,  $wR(F^2) = 0.249$ , maximal/minimal residual electron density 1.12 /--0.58 e Å<sup>-3</sup>. The precision of structure analysis is hampered by the disorder of PF<sub>6</sub><sup>-</sup> anions as well as solvent molecules. PLATON/ SQUEEZE procedure was used to correct the diffraction data for the presence of the disordered solvent.

#### [rac-5][TfO]<sub>2</sub> (CCDC 829267):







Single crystals suitable for X-ray analysis were grown *via* slow diffusion of ethylacetate into an acetone solution of [*rac*-5][TfO]<sub>2</sub>.

Crystal data for [rac-5][TfO]<sub>2</sub>: C<sub>27</sub>H<sub>26</sub>N<sub>2</sub>·2(CF<sub>3</sub>O<sub>3</sub>S), M = 676.65, m.p. = 337-339 °C; Monoclinic, space group  $P2_1/c$  (No 14), a = 9.0740 (6) Å, b = 16.5460 (11) Å, c = 20.7090 (17) Å,  $\beta = 109.934$  (6)°; Z = 4,  $D_x = 1.538$  Mg m<sup>-3</sup>;  $\mu$ (Mo-K<sub>a</sub>) = 0.27 mm<sup>-1</sup>. dimensions of colorless crystal 0.26 × 0.21 × 0.07mm;

X-ray data were measured on a Bruker APEX-II CCD with Mo  $K_{\alpha}$  radiation, T = 150 (2) K;  $\theta_{max} = 27.5^{\circ}$ ; 56411 diffractions collected, 6718 independent ( $R_{int} = 0.102$ ); Absorption correction type: none. Refinement method: full-matrix least-squares based on  $F^2$ , 406 parameters, goodness of fit 1.08, final R indices  $R [I > 2\sigma(I)] = 0.042$ ,  $wR(F^2) = 0.112$ , maximal/minimal residual electron density 0.43/-0.62 e Å<sup>-3</sup>.

#### $[S_a, R_a-4][(R, R)$ -dibenzoyl tartrate]<sub>2</sub> (CCDC 828959):



Single crystals suitable for X-ray analysis were grown *via* slow evaporation of methanol from a methanolwater solution of  $[S_a, R_a-4][(R, R)$ -dibenzoyl tartrate]<sub>2</sub> at 9 °C.

Crystal data for  $[S_a, R_a - 4][(R, R)$ -dibenzoyl tartrate]<sub>2</sub>: C<sub>63</sub>H<sub>55</sub>N<sub>2</sub>O<sub>17.5</sub>, M<sub>r</sub> = 1120.09, m.p. = 186-187 °C; Monoclinic, space group C2, a = 24.233(16) Å, b = 11.685 (8) Å, c = 20.507 (13) Å,  $\beta = 111.491$ (11)°; Z = 4,  $D_x = 1.377$  Mg m<sup>-3</sup>;  $\mu$ (Mo-K<sub>a</sub>) = 0.101 mm<sup>-1</sup>. dimensions of colorless crystal 0.1 × 0.1 × 0.01 mm; X-ray data were measured on a Bruker-Nonius FR 591 with MoK $\alpha$  radiation, T = 100 (2) K;  $\theta_{max} =$ 25.55°; 7636 diffractions collected, 4149 independent ( $R_{int} = 0.1296$ ); Absorption correction type: empirical. Refinement method: full-matrix least-squares based on  $F^2$ , 735 parameters, goodness of fit 0.998, final R indices  $R[I > 2\sigma(I)] = 0.0649$ ,  $wR(F^2) = 0.1185$ , maximal/minimal residual electron density 0.53/-0.30 e Å<sup>-3</sup>. The benzoyl group of anion A is disordered over two positions with an occupancy ratio of 45/55. As a result water molecule 2 is also disordered over three positions in which Ow2' is placed on a two-fold axis (Wyckoff position 2*a*) and O2w is generated by symmetry. Consequently, they were modeled with a partial occupancy of 0.225/0.275, respectively. All hydrogen atoms have been placed in calculated positions. Hydrogen atoms of the carboxylate groups of the anion molecules have been modeled with a partial occupancy of 0.5.

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# Preparation of X-ray quality crystal of the optically pure helquat [*P*-5][ClO<sub>4</sub>]<sub>2</sub> starting from [*P*-5][TfO]<sub>2</sub>

(-)-[P-**5**][TfO]<sub>2</sub> (8 mg, 11.8 µmol) was mixed with 3 mL of demineralized H<sub>2</sub>O. The sample did not fully dissolve. A 0.1M aqueous solution of NaClO<sub>4</sub> (2 mL) was added. From this mixture water was removed on a rotary evaporator (bath temperature max 50 °C). The residue was then mixed with acetone (1 mL) and sonicated. As there were some undissolved particles left, they were removed by filtration *via* syringe and needle equipped with a pad of cotton-wool. The filtrate was directly used to set up the crystallization. Crystals of sufficient X-ray quality formed in a few days by diffusion of (*i*-Pr)<sub>2</sub>O into the solution of helquat [P-**5**][ClO<sub>4</sub>]<sub>2</sub> in acetone.

Crystal data for  $[P-5][ClO_4]_2$ :  $C_{27}H_{26}N_2 \cdot 2(ClO_4) \cdot H_2O$ , M = 595.41, m.p. = 222 °C (decomposition); Orthorhombic, space group  $P2_12_12_1$  (No 19), a = 11.0841 (2) Å, b = 13.3658 (2) Å, c = 17.3210 (3) Å, Z = 4,  $D_x = 1.541$  Mg m<sup>-3</sup>;  $\mu$ (Mo-K<sub>a</sub>) = 2.81 mm<sup>-1</sup>. dimensions of colorless crystal 0.26 × 0.23 × 0.14 mm; X-ray data were measured on a Xcalibur, Atlas, Gemini ultra diffractometer with Cu  $K_a$  radiation, T = 120 (2) K;  $\theta_{max} = 62.3^{\circ}$ ; 41492 diffractions collected, 4355 independent ( $R_{int} = 0.030$ ); Absorption correction type: empirical, T<sub>min</sub> = 0.489, T<sub>max</sub> = 1.000. Refinement method: full-matrix least-squares based on  $F^2$ , 361 parameters, goodness of fit 1.07, final R indices R [ $I > 2\sigma(I)$ ] = 0.030,  $wR(F^2) = 0.091$ , maximal/minimal residual electron density 0.32/-0.63 e Å<sup>-3</sup>.

# **11) References**

- 1 D. B. Amabilino, P. R. Ashton, A. S. Reder, N. Spencer and J. F. Stoddart, *Angew. Chem. Int. Ed. Engl.*, 1994, **33**, 1286.
- 2 In the current procedure homocoupling of the starting ethynylpyridine is suppressed, facilitating purification. See also: L. Severa, L. Adriaenssens, J. Vávra, D. Šaman, I. Císařová, P. Fiedler and F. Teplý, *Tetrahedron*, 2010, **66**, 3537.
- 3 For the first generation procedure complicated by homocoupling, see: L. Adriaenssens, L. Severa, T. Šálová, I. Císařová, R. Pohl, D. Šaman, S. V. Rocha, N. S. Finney, L. Pospíšil, P. Slavíček and F. Teplý, *Chem. Eur. J.*, 2009, **15**, 1072. This procedure was adapted from: E. A. Reddy, D. K. Barange, A. Islam, K. Mukkanti and M. Pal, *Tetrahedron*, 2008, **64**, 7143.
- 4 M. Hanack, K. A. Fuchs and C. J. Collins, J. Am. Chem. Soc., 1983, 105, 4008.
- 5 C. D. Bedford, R. N. Harris, R. A. Howd, D. A. Goff, G. A. Koolpe, M. Petesch, I. Koplovitz, W. E. Sultan and H. A. Musallam, *J. Med. Chem.*, 1989, **32**, 504.
- 6 L. Severa, D. Koval, P. Novotná, M. Ončák, P. Sázelová, D. Šaman, P. Slavíček, M. Urbanová, V. Kašička and F. Teplý, *New J. Chem.*, 2010, **34**, 1063.
- 7. V. Kašička, Z. Prusík, P. Sázelová, E. Brynda and J. Stejskal, *Electrophoresis*, 1999, 20, 2484.
- 8. V. Šolínová, V. Kašička, D. Koval, T. Barth, A. Ciencialová and L. Žáková, *J. Chromatogr. B*, 2004, **808**, 75.
- 9. D. Koval, L. Severa, L. Adriaenssens, J. Vávra, F. Teplý and V. Kašička, *Electrophoresis*, 2011, in print.
- (a) P. Sehnal, Z. Krausová, F. Teplý, I. G. Stará, I. Starý, L. Rulíšek, D. Šaman and I. Císařová, J. Org. Chem., 2008, 73, 2074; (b) A. Andronova, F. Szydlo, F. Teplý, M. Tobrmanová, A. Volot, I. G. Stará, I. Starý, L. Rulíšek, D. Šaman, J. Cvačka, P. Fiedler and P. Vojtíšek, *Collect. Czech. Chem. Commun.*, 2009, 74, 189.
- 11. (a) S. Grimme, J. Comp. Chem., 2004, 25, 1463; (b) S. Grimme, J. Comp. Chem., 2006, 27, 1787.
- 12. H. Valdés, V. Klusák, M. Pitoňák, O. Exner, I. Starý, P. Hobza and L. Rulíšek, J. Comput. Chem., 2008, 29, 861.
- (a) R. Ahlrichs, M. Bär, M. Häser, H. Horn and C. Kölmel, *Chem. Phys. Lett.*, 1989, 162, 165; (b) TURBOMOLE V6.1 2009, a development of University of Karlsruhe and Forschungszentrum Karlsruhe GmbH, 1989-2007, TURBOMOLE GmbH, since 2007; available from http://www.turbomole.com.
- 14. J. P. Perdew, K. Burke and M. Ernzerhof, Phys. Rev. Lett., 1996, 77, 3865.
- (a) P. J. Stephens, F. J. Devlin, C. F. Chabalowski and M. J. Frisch, J. Phys. Chem., 1994, 98, 11623; (b) A. D. Becke, J. Chem. Phys., 1993, 98, 5648; (c) C. T. Lee, W. T. Yang and R. G. Parr, Phys. Rev. B, 1988, 37, 785; (d) A. D. Becke, Phys. Rev. A, 1988, 38, 3098.
- 16. K. Eichkorn, O. Treutler, H. Öhm, M. Häser and R. Ahlrichs, Chem. Phys. Lett., 1995, 240, 283.
- 17. K. Eichkorn, F. Weigen, O. Treutler and R. Ahlrichs, *Theor. Chim. Acta*, 1997, 97, 119.
- 18. A. Schäfer, C. Huber and R. Ahlrichs, J. Chem. Phys., 1994, 100, 5829.
- 19. A. Klamt and G. Schuurmann, J. Chem. Soc., Perkin Trans. 2, 1993, 799.
- 20. A. Schäfer, A. Klamt, D. Sattel, J. C. W. Lohrenz and F. Eckert, *Phys. Chem. Chem. Phys.*, 2000, **2**, 2187.
- 21. F. Jensen, Introduction to Computational Chemistry, John Wiley & Sons, New York, 1999.
- 22. I. Tinoco, Jr. and D. H. Turner, J. Am. Chem. Soc., 1976, 98, 6453.

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# 12) <sup>1</sup>H and <sup>13</sup>C NMR spectra

# Pent-4-ynyl trifluoromethanesulfonate (7)



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# Hex-5-ynyl trifluoromethanesulfonate (8)



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## Cationic diyne salt 9



#### Teplý et al., Electronic Supplementary Information

# Cationic triyne salt 1



#### Teplý et al., Electronic Supplementary Information

# Racemic helquat [rac-2][TfO]<sub>2</sub>



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# Cationic diyne salt 10





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# Racemic helquat [rac-5][TfO]<sub>2</sub>



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# Racemic saddlequat [rac-4][TfO]<sub>2</sub>



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#### Mixture of two diastereomeric saddle quat salts $[rac-4][(R,R)-dibenzoyl tartrate]_2$



#### Diastereomerically pure saddle quat salt (+)-[ $S_a$ , $R_a$ -4][(R,R)-dibenzoyl tartrate]<sub>2</sub>



# Comparison of diagnostic regions of NMR spectra of helquat [rac-5][TfO]<sub>2</sub> and saddlequat

# [rac-4][TfO]<sub>2</sub>

A) in acetone- $d_6$  (600 MHz)







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Figure 1 Diagnostic ROESY correlations in saddle quat [4][TfO]<sub>2</sub> compared with helquats [2][TfO]<sub>2</sub> and [5][TfO]<sub>2</sub>