Pergamon

Tetrahedron, Vol. 53, No. 25, pp. 8651-8664, 1997

0040-4020/97 $17.00 + 0.00

PII: S0040-4020(97)00535-8

Chiral Acetylene Thioethers: Synthesis and Pauson-Khand Reactions.

Elvira Montenegro, Marta Poch, Albert Moyano, Miquel A. Pericàs*, Antoni Riera*

Unitat de Recerca en Síntesi Asimètrica. Departament de Química Orgànica, Facultat de Química, Universitat de Barcelona. Martí i Franquès, 1-11, 08028 Barcelona, Spain.

Fax: 3-43-3397878. E-mail: are@ursa.qo.ub.es, mpb@ursa.qo.ub.es

Abstract. Chiral acetylene thioethers have been prepared in excellent yields from the corresponding thiols. The procedure involves the treatment of the corresponding thiolate with 2-bromo-1,1-diethoxyethane followed by double elimination with LDA and, in some cases, alkylation of the acetylide with alkyl or ω-alkenyl iodides. These compounds have been tested in both intra- and intermolecular Pauson-Khand reactions. This study clearly shows that acetylenic thioethers can be excellent substrates for asymmetric versions of this reaction. © 1997 Elsevier Science Ltd.

INTRODUCTION

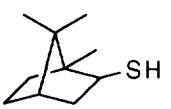
The Pauson-Khand reaction has emerged as one of the most powerful tools in cyclopentenone synthesis.[1] Although in recent years several enantioselective methodologies have been developed,[2-5] only those based on the chiral auxiliary approach have already been applied to the synthesis of complex natural products such as (+)-hirsutene,[4a] (+)-β-cuparenone,[6] brefeldin A,[7] and nor-pentalenene.[8] In all of these cases the inductor was a chiral alcohol placed in the starting material as an enol[4] or ynol[5] ether. 1-Alkynyl sulphides, the sulphur analogues of acetylene ethers, are stable compounds known since the fifties[9] but, with the only remarkable exception of phenylthioacetylene,[10] their use in synthesis has been scarce. An important limitation in the use of acetylene ethers as educts for Pauson-Khand reactions is the need of steric shielding of the triple bond in order to achieve the preparation of their dicobalt hexacarbonyl complexes in high yield. In the case of the terminal acetylene ethers this problem has been solved by the use of a three step protocol in the synthesis of the hexacarbonyl complexes.[11] We reasoned that chiral acetylene thioethers, which usually exhibit higher stability against hydrolysis and polymerisation than their oxygenated analogues, could offer some advantages such as easier preparation of the complexes, higher reaction yields and more versatile chemical manipulation of the adducts. We report herein the preparation of new chiral acetylene thioethers and a study of their use in asymmetric Pauson-Khand reactions.

RESULTS AND DISCUSSION.

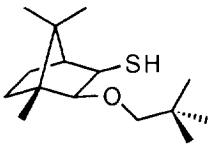
A) Synthesis of Chiral Acetylene Thioethers.

A literature survey showed many synthetic procedures for the preparation of acetylene thioethers that can be summarised as follows: elimination reactions,[9,10,12] nucleophilic substitution of a terminal alkali metal acetylide on several sulphur electrophiles (elemental sulphur, disulphides, sulfinyl chlorides,

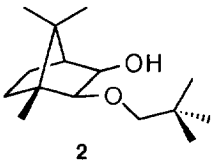
benzenthiosulfonates...),[13] nucleophilic substitution of a thiolate ion on a halogenated acetylenic carbon,[14] alkylation of alkynyl thiolates[15] and isomerization reactions.[16] However, in spite of the amount of synthetic methodology that has been developed, only simple alkyl or aryl acetylene thioethers have been described so far. The need for a practical high yield process suitable for the synthesis of acetylene thioethers derived from valuable thiols prompted us to apply to our target compounds the methodology developed by Cookson and co-workers[10a] for the preparation of phenylthioacetylene. This method combines the advantages of high yield of the individual steps and minimisation of the consumed amount of the expensive chiral thiols. We selected as starting materials the camphor derived thiols **1a** and **1b** which possess a rigid bornane skeleton that we have employed with success in the diastereoselective Pauson-Khand chemistry of the corresponding *O*-alkyl enol and ynol ethers.[4,5] (1*S-exo*)-2-Bornanethiol **1a,** being readily available in multigram quantities from (-)-borneol,[17] would allow optimization of reaction conditions. (1*R*,2*S*,3*R*)-2-Neopentyloxy-1,7,7-trimethylbicyclo[2.2.1]heptane-3-thiol[18] **1b**, the sulphur analogue of the Oppolzer's chiral auxiliary 3-hydroxyisobornyl neopentyl ether **2**,[19] is in turn a representative example of a sterically based inductor.



1a

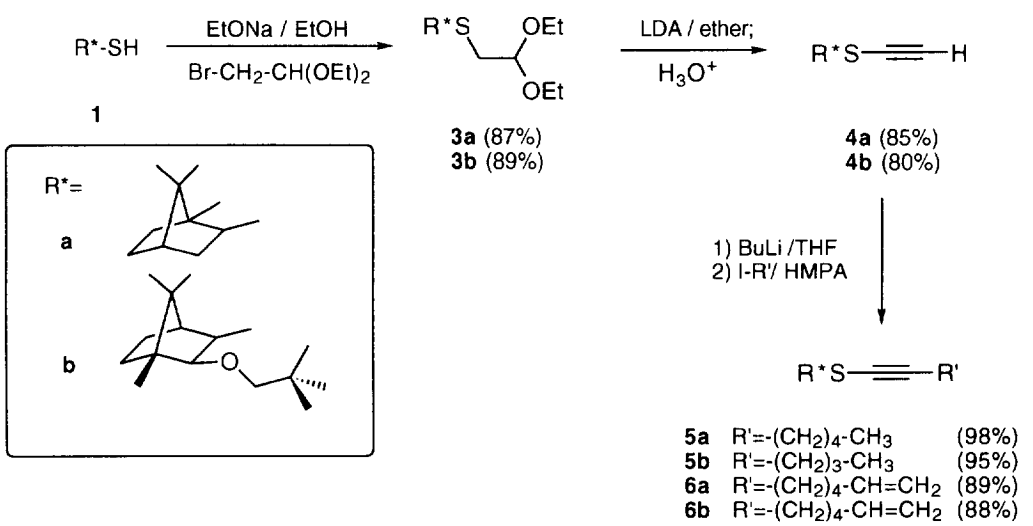


1b



2

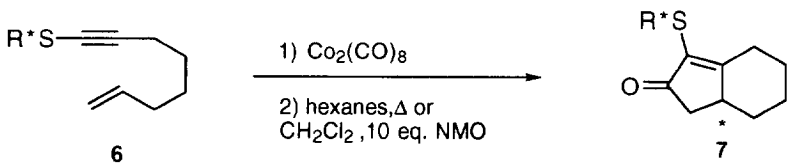
The synthetic procedure for the preparation of chiral acetylenic thioethers is shown in Scheme 1. The reaction of the sodium thiolates derived from chiral thiols **1** with 2-bromoacetaldehyde diethylacetal in ethanol proceeded with excellent yields to afford the corresponding 2-(R*-thio)-1,1-diethoxyethanes **3**. A subsequent double elimination with LDA in diethyl ether yielded the ethynyl thioethers **3** also in excellent yields. These compounds can be easily alkylated by treating the lithium acetylide in THF with an alkyl or ω-alken-1-yl iodide in HMPA. In this way, internal alkynes **4** or enynes **5** bearing the chiral ethynyl sulphide function were prepared. (Scheme 1).



Scheme 1

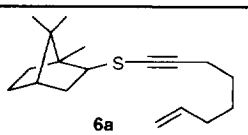
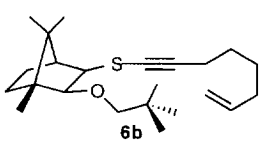
B) Intramolecular Pauson-Khand reactions.

With the chiral enynes **6** in hand the intramolecular Pauson-Khand reaction was first studied. The intermediate dicobalt hexacarbonyl complexes were cleanly formed (TLC) by treatment of the corresponding enynes with a slight excess of dicobalt octacarbonyl in an appropriate solvent (hexanes or methylene chloride). The solution of the complex was then submitted to both nowadays standard conditions for Pauson-Khand reactions: Thermal activation[1] and *N*-oxide promoted reaction.[20] Thermal reactions were performed in hexanes, the solution of the complex being increasingly warmed until a new UV active product could be observed by TLC and maintaining that temperature until the total consumption of the hexacarbonyl complex. Chromatography of the crude allowed the isolation of bicyclic adducts **7** in good yields (Table 1). *N*-oxide promoted reactions were performed by adding 10-12 equivalents of *N*-methylmorpholine *N*-oxide hydrate (NMO) to the solution of the complex in methylene chloride and took place with slightly lower yields (Table 1). Whereas the reactions of **6a** took place with disappointingly low selectivity, a slight diastereomeric preference was observed in the case of **6b**.



6 7

Table 1. Intramolecular Pauson-Khand reactions of R*-thioenynes **6**.

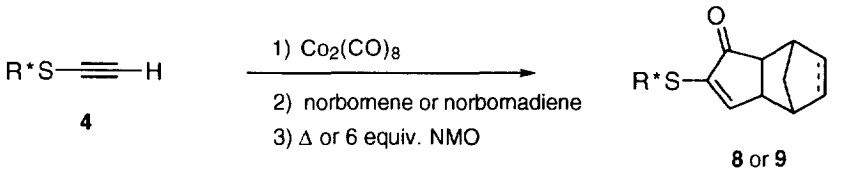
Entry	Starting R*thioenyne	Reaction conditions[a] (temperature, time)	Product (yield, d.r.)[b]
1		A, 65 °C, 12h	**7a** (55%, 1.1:1)
2		B, 0 °C, 11h	**7a** (50%, 1.1:1)
	6a		
3		A, 65 °C, 42h	**7b** (60%, 1.4:1)
4		B, -20 °C, 48h	**7b** (47%, 1.3:1)
	6b		

[a] Conditions A: stirring the preformed dicobalt hexacarbonyl complex in hexanes at the specified temperature. Conditions B: addition of 10 equiv. of NMO to the CH_2Cl_2 solution of the dicobalt hexacarbonyl complex at the specified temperature. [b] By ^{13}C NMR.

C) Intermolecular Pauson-Khand Reactions.

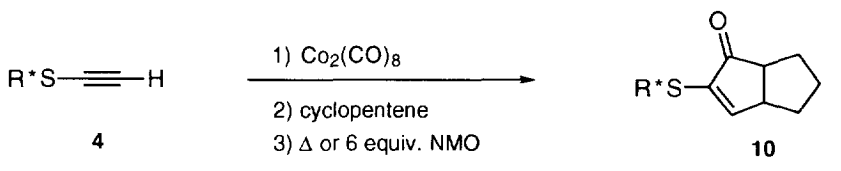
As we have already mentioned, the preparation of dicobalt hexacarbonyl complexes of terminal alkoxyacetylenes requires a three step process (protection with trimethylsilyl chloride, complexation and deprotection) since the direct reaction leads to substantial polymerisation of the starting material and takes place in extremely low yields. In the case of acetylene thioethers, the only precedent described in the literature was the preparation of the hexacarbonyl cobalt complex of phenylthioacetylene reported by P.L. Pauson in 1984 in 33% yield. [21] In the case of acetylene thioethers **4**, the complexation reaction proceeded smoothly and, although the complex was not isolated, no polymerisation nor side reactions could be observed by TLC analysis. The Pauson-Khand reactions were then performed by treating the solutions of the complexes with the

corresponding alkenes under thermal or chemical (NMO) conditions. As usual in the Pauson-Khand reaction, only *exo* adducts were formed and the reactions were always regioselective, the alkylthio group being placed α to the carbonyl in the cyclopentenone ring. With strained olefins, like norbornene and norbornadiene, yields were excellent under *N*-oxide promoted conditions and somewhat lower with thermal activation (Table 2). In all cases the cycloadducts were isolated as mixtures of diastereomers not separable by chromatography. Reactions with the complex derived from acetylene thioether **4a** were not selective at all, while inductor **1b** induced some selectivity under *N*-oxide promoted conditions (entries 8 and 10, Table 2).



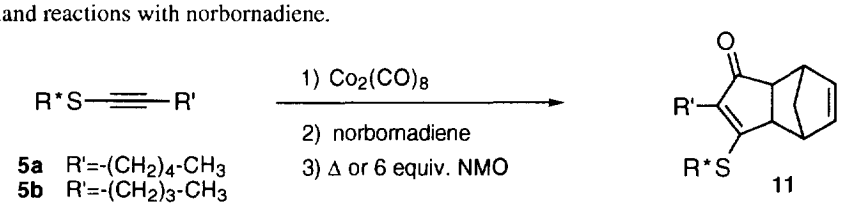
4 **8** or **9**

Pauson-Khand reactions with cyclopentene are usually much more difficult than with strained olefins. Nevertheless, cobalt complexes derived from acetylene thioethers **4a** and **4b** reacted with cyclopentene to afford the corresponding adducts **10a** and **10b** in moderate to good yields. In the case of **4b**, moreover, a remarkable 4.6:1 diastereoselectivity was observed in the NMO promoted reaction (Table 2, entry 12). It is worth noting that the Pauson-Khand reaction with the analogous oxygenated inductor **2** affords the corresponding cycloadduct in 40% yield and with complete lack of selectivity.[5b]



4 **10**

Intermolecular Pauson-Khand reactions with internal acetylene ethers have not been extensively studied because preliminary experiments showed that the reactions proceeded with opposite regioselectivity and complete lack of stereoselectivity.[22] Moreover, low overall yields were obtained in compounds without sufficient steric protection around the triple bond. The fact that the complexation reaction with terminal alkynyl sulphides proceeded very cleanly, prompted us to study the intermolecular Pauson-Khand reactions with internal alkynyl sulphides. Consequently, thioalkynes **5** were submitted to thermal and *N*-oxide promoted Pauson-Khand reactions with norbornadiene.



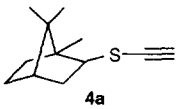
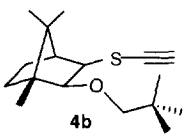
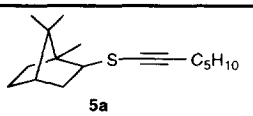
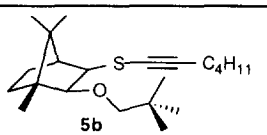
5a R'=-$(CH_2)_4$-CH_3
5b R'=-$(CH_2)_3$-CH_3

11

According to our expectations, good yields of cycloadducts **11** were obtained under both types of conditions. The reaction was again totally regioselective but afforded the isomer with the alkylthio in β to the carbonyl in the alkylthiocyclopentenone ring, in opposition to what is observed with terminal alkynes. As could be anticipated, reactions with compounds derived from thiol **1a** did not give any stereoselectivity. However, to our satisfaction, in the case of compound **5b** a very promising 4.1:1 d.r. was observed in

cycloadduct **11b**. Unfortunately the low polarity of these adducts makes the separation of the diastereomers by normal chromatography extremely difficult.

Table 2. Intermolecular Pauson-Khand reactions of R*-thioalkynes **4** and **5** with alkenes.

Entry	Starting R*thioalkyne	Alkene	Reaction conditions[a] (temperature, time)	Product (yield, d.r.)[b]
1	 **4a**	norbornadiene	A, 50 °C, 1h	**8a** (56%, 1:1)
2		norbornadiene	B,-20 °C, 1h	**8a** (89%, 1:1)
3		norbornene	A, 25 °C, 3d	**9a** (74%, 1:1)
4		norbornene	B, -20 °C, 1h	**9a** (79%, 1:1)
5		cyclopentene	A, 70 °C, 48h	**10a** (62%, 1:1)
6		cyclopentene	B, -20 °C, 3h	**10a** (33%, 1.1)
7	 **4b**	norbornadiene	A, 25 °C, 24h	**8b** (68%, 1:1)
8		norbornadiene	B, -20 °C, 16h	**8b** (85%, 1.7:1)
9		norbornene	A, 25 °C, 26h	**9b** (81%, 1.5:1)
10		norbornene	B, -20 °C, 7h	**9b** (98%, 1.6:1)
11		cyclopentene	A, 80 °C, 48h	**10b** (58%, 2.2:1)
12		cyclopentene	B, -20 °C, 28h	**10b (48%, 4.6:1)**
13	 **5a**	norbornadiene	A, 70 °C, 3h	**11a** (56%, 1:1)
14		norbornadiene	B, -20 °C, 25h	**11a** (52%, 1:1)
15	 **5b**	norbornadiene	A, 65 °C, 22h	**11b** (76%, 2.1:1)
16		norbornadiene	B, -20 °C, 48h	**11b (58%, 4.1:1)**

[a] Conditions A: stirring the preformed dicobalt hexacarbonyl complex in hexanes or toluene at the specified temperature. Conditions B: addition of 6 equiv. of NMO to the solution of the dicobalt hexacarbonyl complex in methylene chloride at the specified temperature. [b] By ^{13}C NMR.

In summary, we have shown that chiral acetylene thioethers can be prepared by treatment of the corresponding thiolate with 2-bromo-1,1-diethoxyethane followed by a double elimination with LDA and, in some cases, alkylation of the corresponding acetylide. By this procedure, multigram quantities of new chiral acetylene thioethers **4** and **5** and thioenynes **6** have been prepared. These compounds have been tested in both intra- and intermolecular Pauson-Khand reactions. It is worth mentioning that the preparation of the hexacarbonyl complexes proceeded without polymerisation even in the case of terminal thioalkynes in sharp contrast to their oxygenated analogues. High to excellent yields have been recorded in the Pauson-Khand reactions of **4**, **5** and **6**. Moreover, in the intermolecular reactions of compounds derived from thiol **1b** remarkable results were obtained: The reaction of terminal thioalkyne **4b** with cyclopentene under *N*-oxide promoted conditions afforded cycloadduct **10** with a diastereomeric ratio of 4.6:1, while the reaction of the

internal acetylene thioether **5b** with norbornadiene yielded cycloadduct **11** with a 4.1:1 diastereomeric ratio. These results clearly show that acetylene thioethers can be excellent substrates for asymmetric Pauson-Khand reactions. Design and synthesis of new chiral thiols able to induce higher diastereoselectivities are currently under study in our laboratories and will be reported in due course.

Acknowledgement. We thank CIRIT-CICYT (Grant QFN 93-4407), DGICYT (PB95-0265) and CIRIT (GRQ93-1083) for financial support. One of us (E.M) thanks CIRIT (Generalitat de Catalunya) for a predoctoral fellowship.

EXPERIMENTAL SECTION.

General. Melting points were determined in an open capillary tube and are uncorrected. Optical rotations were measured at room temperature (22-25°C) on a Perkin-Elmer 241 MC polarimeter (Concentration in g/100 mL). Infrared spectra were recorded on a Perkin-Elmer 681, or on a Nicolet 510 FT-IR. NMR spectra were acquired on Varian XL-200 or Varian-Unity-300 instruments. ^{1}H-NMR were recorded at 200 or 300 MHz (s=singlet, d=doublet, t=triplet, q=quartet, dt= double triplet, m=multiplet and b=broad). ^{13}C-NMR were recorded at 50.3 MHz or 73.4 MHz. Carbon multiplicities have been assigned by DEPT experiments. In all cases, chemical shifts are in ppm downfield of TMS (referenced to an internal standard for ^{1}H NMR, and to the central signal of $DCCl_3$ for ^{13}C NMR). In the case of inseparable diastereomeric mixtures, the signals corresponding to major or minor diastereomer are indicated by maj and min respectively if can be assigned. In a 1:1 mixture the set of signals corresponding to one diastereomer is indicated by an asterisk. Diastereomeric ratios were determined by ^{13}C NMR. Mass spectra were recorded on a Hewlett-Packard 5890 instrument at 70 eV ionising voltage; ammonia was used for chemical ionisation (CI). Elemental analyses were performed by the "Servei d'Anàlisis Elementals del CSIC de Barcelona". THF and diethyl ether were distilled from sodium benzophenone ketyl. All reactions were performed in oven-dried glassware under N_2 atmosphere. Reaction progress was monitored by TLC (Merck DC-Alufolien KIESELGEL 60 F254) eluting with hexanes/ethyl acetate mixtures.

General Procedure A. Preparation of 2-(R*-thio)-1,1-diethoxyethanes 3.

To a stirred suspension of sodium ethoxide in ethanol (from 11 mmol of sodium in 30 mL of ethanol) was added dropwise a solution of the corresponding thiol **1** (10 mmol) in ethanol (9 mL). After 45 minutes of stirring at room temperature, 2-bromo-1,1-diethoxyethane (1.7 mL, 11 mmol) was added. The reaction mixture was heated at reflux for 3 h. and then poured into ice/water. The aqueous layer was extracted with methylene chloride and the combined organic phases were dried (Na_2SO_4) and evaporated. The crude product was purified by column chromatography on Et_3N pre-treated silica gel (2.5% v/v) eluting with diethyl ether/hexane mixtures of increasing polarity to yield the corresponding 2-(R*-thio)-1,1-diethoxyethanes **3**.

(1*S*, 2*S*, 4*S*)-2-(2,2-Diethoxyethylsulfanyl)-1,7,7-trimethylbicyclo[2.2.1]heptane 3a.

The general procedure A, applied to **1a** afforded **3a** (87%) as an oil: $[\alpha]^{23}_D$=+ 38.8 (*c* 2.12, $CHCl_3$) . IR (film) ν_{max} = 2920, 2860, 1450, 1370, 1360, 1120, 1050 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$) δ 4.54 (t, J= 5.8 Hz, 1H), 3.72-3.38 (m, 4H), 2.77 (dd, J= 10 Hz, J= 7 Hz, 1H), 2.66 (dd, J= 5.6 Hz, J= 4.5 Hz, 2H), 1.95-1.50 (m, 5H), 1.28-1 (m, 2H), 1.17 (t, J= 7Hz, 6H), 0.95 (s, 3H), 0.91 (s, 3H), 0.76 (s, 3H); ^{13}C NMR (50

MHz, $CDCl_3$) δ 103.2 (CH), 61.8 (CH_2), 61.7 (CH_2), 54.7 (CH), 49.2 (C), 47.2 (C), 45.7 (CH), 40.6 (CH_2), 38.3 (CH_2), 37.6 (CH_2), 27.2 (CH_2), 20.3 (CH_3), 20.1 (CH_3), 15.2 (CH_3), 13.8 (CH_3).; MS (C.I.-NH_3) m/e = 304 (M^++18, 2%), 287 (M^++1, 1%), 243 ($M(^{34}S)^+$-45, 4%), 241 (M^+-45, 60%), 214 ($M(^{34}S)^+$-74, 7%), (212 (M^+-74, 100%), 137 ($C_{10}H_{17}^+$, 18%).

(1*S*,2*R*,3*S*,4*R*)-3-(2,2-Diethoxyethylsulfanyl)-2-(2,2-dimethylpropoxy)-1,7,7-trimethylbicyclo [2.2.1]heptane 3b.

The general procedure A, applied to **1b** afforded **3b** (89%) as an oil: $[\alpha]^{23}_D$ = - 63.8 (*c* 1.31, $CHCl_3$); IR (film) ν_{max} = 2940, 2860, 1470, 1360, 1115, 1100, 1075, 1050, 1000 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 4.6 (t, J= 6.1 Hz, 1H), 3.72-3.49 (m, 4H), 3.45, 2.94 (AB, J= 7.7 Hz, 2H), 3.23, 3.09 (AB, J= 7.7 Hz, 2H), 2.69-2.66 (m, 2H), 2.85-1.3 (m, 4H), 1.22 (t, J= 7 Hz, 6H), 1.17 (s, 3H), 1.04-0.99 (m, 1H), 0.93 (s, 9H), 0.89 (s, 3H), 0.77 (s, 3H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 103.6 (CH), 88.9 (CH), 83.6 (CH_2), 61.9 (CH_2), 61.8 (CH_2), 56.7 (CH), 51.9 (CH), 50.5 (C), 46.9 (C), 36.4 (CH_2), 33.5 (CH_2), 32.7 (C), 28.6 (CH_2), 26.9 (CH_3), 21.4 (CH_3), 21.2 (CH_3), 15.3 (CH_3), 12.02 (CH_3).; MS (C.I.-NH_3) m/e = 390 (M^++18, 7%), 373 (M^++1, 5%), 327 (M^+-45, 18%), 300 ($M(^{34}S)^+$-74, 7%), 298 (M^+-74, 100%)

General Procedure B. Preparation of acetylene thioethers 4.

To a cooled (0°C) solution of diisopropylamine (2.4 mL, 16.8 mmol) in ether (15 mL) was *n*-BuLi (11 mL, 1.5 M in hexanes, 16.5 mmol). After stirring 45 minutes at room temperature, the resulting LDA solution was cooled to -60 °C and a solution of the corresponding 2-(R^*-thio)-1,1-diethoxyethane **3** (5.25 mmol) in ether (7 mL) was added. The temperature was allowed to warm to 0 °C and the stirring was maintained during 3 h. The reaction was quenched by addition of saturated NH_4Cl solution. The aqueous layer was extracted with CH_2Cl_2 and the combined organic phases were dried (Na_2SO_4) and evaporated. The crude product was purified by column chromatography on Et_3N pre-treated silica gel (2.5% v/v) eluting with diethyl ether/hexane mixtures of increasing polarity to yield the acetylene thioether **4**.

(1*S*, 2*S*, 4*S*)-2-Ethynylsulfanyl-1,7,7-trimethylbicyclo[2.2.1]heptane 4a.

The general procedure B, applied to **3a** afforded **4a** (85%) as an oil: $[\alpha]^{23}_D$ = + 83.2 (*c* 1.85, $CHCl_3$); IR (film) ν_{max} = 3300, 2950, 2710, 2010, 1450 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 3.20 (dd, J= 8.7 Hz, J'= 6.1 Hz, 1H), 2.79 (s, 1H), 2.05-1.61 (m, 5H), 1.25-1.08 (m, 2H), 1.07 (s, 3H), 0.93 (s, 3H), 0.84 (s, 3H). ^{13}C NMR (50 MHz, $CDCl_3$) δ 81.2 (CH), 58.4 (CH), 49.8 (C), 47.5 (C), 38.9 (CH_2), 38.01 (CH_2), 27.1 (CH_2), 20.2 (CH_3), 20.1 (CH_3), 13.4 (CH_3).; MS (C.I. - NH_3) m/e = 212 (M^++18, 6%), 154 ($C_{10}H_{17}^+$+17, 62%), 137 ($C_{10}H_{17}^+$, 100%).

(1*S*,2*R*,3*S*,4*R*)-2-(2,2-Dimethylpropoxy)-3-ethynylsulfanyl-1,7,7-trimethylbicyclo[2.2.1]heptane 4b.

The general procedure B, applied to **3b** (11 mmol) afforded **4b** (80% yield, 84% conversion) as a white solid: mp = 43-44 °C; $[\alpha]^{23}_D$ = - 99.6 (*c* 1.76, $CHCl_3$); IR (film) ν_{max} = 3320, 2960, 2880, 2060, 1480, 1400, 1105 cm^{-1}. ^1H NMR (200 MHz, $CDCl_3$) δ 3.52, 3.02 (AB, J= 7.7 Hz, 2H), 3.37, 3.31 (AB, J= 7.8 Hz, 2H), 2.75 (s, 1H), 2.1-1.4 (m, 4H), 1.19 (s, 3H), 1.07-0.95 (m, 1H), 0.92 (s, 9H), 0.91 (s, 3H), 0.81 (s, 3H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 88.02 (CH), 84.05 (CH_2), 80.9 (CH), 78 (C), 60.0 (CH), 50.9 (CH), 50.86 (C), 47.1 (C), 33.2 (CH_2), 32.8 (C), 28.3 (CH_2), 26.8 (CH_3), 21.5 (CH_3), 21.02 (CH_3), 11.8 (CH_3).; MS (C.I. - CH_4) m/e = 309 (M^++29, 2%), 283 ($M(^{34}S)^+$+1, 7%), 281 (M^++1, 100%), 223 (M^+-57, 3%), 211 (M^+-69,

36%), 195 (M(^{34}S)$^+$-87, 29%), 193 (M$^+$-87, 100%).; Elemental Analysis: Calc. C, 72.8%; H, 10.06%; S, 11.43%. Found C, 72.78%; H, 10.00%; S, 11.34%.

General Procedure C. Synthesis of Internal Acetylene Thioethers 5 and 6.

To a solution of the terminal thioether **4** (0.5 mmol) in THF (1 mL) was added *n*-BuLi (0.6 mmol) in hexanes (1.49 M) at 0 °C. After 30 minutes stirring the corresponding alkyl or alkenyl iodide (2 mmol) in HMPA (2 mL) was added *via* cannula. The reaction mixture was allowed to warm up to room temperature and stirred 48 h. Then, saturated solution of NH_4Cl was added and the aqueous layer extracted with ether. The combined organic phases were washed with brine, dried (Na_2SO_4) and evaporated. The crude product was purified by column chromatography on Et_3N pre-treated silica gel (2.5% v/v) eluting with diethyl ether/hexane mixtures of increasing polarity to yield the internal acetylene thioethers **5** or **6**.

(1*S*, 2*S*, 4*S*)-2-(Hept-1-ynylsulfanyl)-1,7,7-trimethylbicyclo[2.2.1]heptane 5a.

The general procedure C, applied to **4a** using *n*-pentyl iodide afforded **5a** in 98% yield as an oil. $[\alpha]^{23}_D$ = + 57.8 (*c* 2.01, $CHCl_3$).IR (film) ν_{max} = 2920, 2840, 2170, 1445 cm^{-1}. ^{1}H-NMR (200 MHz, $CDCl_3$) δ 3.11 (dd, J= 8.6 Hz, J'= 6.2 Hz, 1H), 2.28 (t, J= 7Hz, 2H), 2-0.75 (m, 16H), 1.06 (s, 3H), 0.92 (s, 3H), 0.83 (s, 3H). ^{13}C-NMR (50 MHz, $CDCl_3$) δ 93.6 (C), 71.3 (C), 58.5 (CH), 49.4 (C), 47.4 (C), 45.6 (CH), 38.7 (CH_2), 38.1 (CH_2), 31.0 (CH_2), 28.5 (CH_2), 27.2 (CH_2), 22.2 (CH_2), 20.2 (CH_3), 20.1 (CH_3), 13.9 (CH_3), 13.4 (CH_3). MS (C.I. - NH_3) m/e = 284 (M(^{34}S)$^+$+18, 9%), 282 (M$^+$+18, 100%), 265 (M$^+$+1, 3%), 154 ($C_{10}H_{17}^+$+17, 76%), 137 ($C_{10}H_{17}^+$, 62%).

(1*S*,2*R*,3*S*,4*R*)-2-(2,2-Dimethylpropoxy)-3-(hex-1-ynylsulfanyl)-1,7,7-trimethylbicyclo[2.2.1] heptane 5b.

The general procedure C, applied to **4b** (0.7 mmol) using *n*-butyl iodide afforded **5b** in 95% yield as an oil. $[\alpha]^{23}_D$ = - 87. 7 (*c* 1.5, $CHCl_3$). IR (film) ν_{max} = 2950, 2870, 2195, 1470, 1455, 1105 cm^{-1}. ^{1}H-NMR (200 MHz, $CDCl_3$,) δ 3.42, 3.29 (AB, J= 7.5 Hz, 2H), 3.39, 2.99 (AB, J= 7.9 Hz, 2H), 2.30 (t, J= 7.5 Hz, 2H), 2.05-1.25 (m, 8H), 1.18 (s, 3H), 1.07-0.95 (m, 1H), 0.91 (s, 12H), 0.89 (s, 3H), 0.8 (s, 3H). ^{13}C-NMR (50 MHz, $CDCl_3$) δ 93.3 (C), 88.2 (CH), 83.9 (CH_2), 70.8 (C), 60.4 (CH), 51.03 (CH), 50.8 (C), 47.04 (C), 33.3 (CH_2), 32.7 (C), 30.9 (CH_2), 28.4 (CH_2), 26.8 (CH_3), 21.9 (CH_2), 21.5 (CH_3), 21.04 (CH_3), 19.8 (CH_2), 13.6 (CH_3), 11.9 (CH_3). MS (C.I.-NH_3) m/e = 356 (M(^{34}S)$^+$+18, 1%), 354 (M$^+$+18, 15%), 339 (M(^{34}S)$^+$+1, 7%), 337 (M$^+$+1, 100%), 251 (M$^+$-85, 15%).

(1*S*, 2*S*, 4*S*)-2-(7-Octen-1-ynylsulfanyl)-1,7,7-trimethylbicyclo[2.2.1]heptane 6a.

The general procedure C, applied to **3a** using 6-iodo-1-hexene afforded **6a** (89%) as an oil: $[\alpha]^{23}_D$= +54.8 (*c* 2.18 $CHCl_3$); IR (film) ν_{max} = 3050, 2930, 2860, 2020, 1635, 1442, 900 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$) δ 5.9-5.7 (m, 1H), 5.1-4.88 (m, 2H), 3.10 (dd, J= 8.6 Hz, J'= 6.2 Hz, 1H), 2.3 (t, J= 7.5 Hz, 2H), 2.1-1.1 (m,13H), 1.05 (s, 3H), 0.92 (s, 3H), 0.82 (s, 3H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 138.5 (CH), 114.5 (CH_2), 93.2 (C), 71.0 (C), 58.5 (CH), 49.5 (C), 47.4 (C), 45.6 (CH), 38.7 (CH_2), 38.0 (CH_2), 33.2 (CH_2), 28.2 (CH_2), 27.9 (CH_2), 27.2 (CH_2), 20.2 (CH_3), 20.1 (CH_3), 19.9 (CH_2), 13.4 (CH_3).; MS (C.I.-NH_3) m/e = 296 (M(^{34}S)$^+$+18, 2%), 294 (M$^+$+18, 40%), 279 (M(^{34}S)$^+$+1, 3%), 277 (M$^+$+1, 54%), 154 ($C_{10}H_{17}^+$+17, 72%), 137 ($C_{10}H_{17}^+$, 100%).

(1*S*,2*R*,3*S*,4*R*)-2-(2,2-Dimethylpropoxy)-3-(7-octen-1-ynylsulfanyl)-1,7,7-trimethylbicyclo[2.2.1] heptane 6b.

The general procedure C, applied to **3b** (0.7 mmol) using 6-iodo-1-hexene afforded **6b** (88%, with a 10% of terminal acetylene **3b**) as an oil: $[\alpha]^{23}_D$ = - 84.6 (*c* 1.95, $CHCl_3$); IR (film) ν_{max} = 3310, 3080, 2960, 2880, 2050, 1650, 1480, 1460, 1390, 1110 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 5.85-5.64 (m, 1H), 5.05-4.92 (m, 2H), 3.42, 2.99 (AB, J= 7.8 Hz, 2H), 3.39, 3.29 (AB, J= 7.6 Hz, 2H), 2.31-1.4 (m, 12H), 1.18 (s, 3H), 1.07-0.95 (m, 1H), 0.91 (s, 9H), 0.89 (s, 3H), 0.79 (s, 3H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 138.6 (CH), 114.5 (CH_2), 93.07 (C), 88.1 (CH), 83.9 (CH_2), 71.09 (C), 60.3 (CH), 50.8 (C), 50.9 (CH), 47.05 (C), 33.2 (CH_2), 32.7 (C), 28.4 (CH_2), 28.3 (CH_2), 27.9 (CH_2), 26.8 (CH_3), 21.5 (CH_3), 21.02 (CH_3), 20.00 (CH_2), 11.9 (CH_3).; MS (C.I.-NH_3) m/e = 380 (M^++18, 8%), 365 ($M(^{34}S)^+$+1, 3%), 363 (M^++1, 41%), 298 (281+17, 43%), 281 (M^+-81, 100%).

General Procedure D. Intramolecular Pauson-Khand Reactions of Acetylene Thioethers. Thermal Activation.

To a solution of acetylene thioether **5** (0.2 mmol) in hexane (5 mL) was added $Co_2(CO)_8$ (0.21 mmol). The reaction mixture was stirred 30 minutes at room temperature. The formation of a red dark colored complex was observed. Then, it was heated at 65°C until no dicobalt hexacarbonyl complex could be observed by TLC (approx 12 h). The solid suspension was filtered through Celite®, and washed thoroughly with CH_2Cl_2. The combined organic extracts were evaporated *in vacuo*. The crude product was purified by column chromatography on Et_3N pre-treated silica gel (2.5% v/v) eluting with diethyl ether/hexane mixtures of increasing polarity to yield bicycloadducts **7**.

General Procedure E. Intramolecular Pauson-Khand Reactions of Acetylene Thioethers. *N*-Oxide Promoted Reaction.

To a solution of acetylene thioether **5** (0.25 mmol) in CH_2Cl_2 was added $Co_2(CO)_8$ (0.25 mmol). The reaction mixture was stirred 30 minutes at room temperature. The formation of a red dark colored complex was observed. The solution was cooled to -20°C and solid NMO (1.3 mmol) was added. The reaction was monitored by TLC until no dicobalt hexacarbonyl complex could be observed by TLC (approx 12 h). The solid suspension was filtered through Celite®, and washed thoroughly with CH_2Cl_2. The combined organic extracts were evaporated *in vacuo*. The crude product was purified by column chromatography on Et_3N pre-treated silica gel (2.5% v/v) eluting with diethyl ether/hexane mixtures of increasing polarity to yield bicycloadducts **7**.

9-[(1*S*, 2*S*, 4*S*)-1,7,7-Trimethylbicyclo[2.2.1]hept-2-ylsulfanyl]bicyclo [4.3.0]non-1(9)-en-8-one 7a.

The general procedure D, applied to **5a** afforded **7a** (55%, 1.1:1 d.r.) as an oil. The general procedure E, applied to **5a,** afforded **7a** (34%, 1.1:1 d.r.) as an oil:

7a. IR (film) ν_{max} = 2900, 2850, 1695, 1590, 1435, 950 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 3.42-3.15 (m, 2H), 2.7-2.55 (m, 2H), 2.2-1 (m, 15H), 1.03 (a), 1.01 (b) (s, 3H), 0.96 (a), 0.93 (b), (s, 3H), 0.80 (s, 3H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 205.5 (C), 183.3 (C),181.9 (C, min), 132.1 (C), 52.6 (CH), 52.4 (CH, min), 49.4 (C), 49.04 (C, min), 47.5 (C), 45.8 (CH), 45.7 (CH, min), 41.6 (CH_2), 41.4 (CH_2, min), 41.4 (CH), 40.7 (CH_2), 40.7 (CH, min), 40.6 (CH_2, min) 39.9 (CH_2), 39.7 (CH_2, min),38.02 (CH_2), 37.8 (CH_2, min), 35.3 (CH_2), 34.9 (CH_2, min), 26.9 (CH_2, min),29.8 (CH_2), 27.1 (CH_2), 26.2 (CH_2, min)25.3 (CH_2), 20.4 (CH_3), 20.2 (CH_3, min),13.8 (CH_3).13.6 (CH_3, min).; MS (C.I.-NH_3) m/e = 324 ($M(^{34}S)^+$+18, 9%), 322

(M^++18, 52%), 307 ($M(^{34}S)^+$+1, 9%), 305 (M^++1, 100%), 169 (M^+-135, 35%), 154 ($C_{10}H_{17}^+$+17, 14%), 137 ($C_{10}H_{17}^+$, 35%).

9-[(1*S*,2*R*, 3*S*, 4*R*)-3-(2,2-Dimethylpropoxy)-4,7,7-trimethylbicyclo[2.2.1]hept-2-ylsulfanyl]bicyclo [4.3.0]non-1(9)-en-8-one 7b.

The general procedure D, applied to **5b** (0.16 mmol), afforded **7b** (60%, 1.4:1 d.r.) as an oil. The general procedure E, applied to **5b** (0.16 mmol), afforded **7b** (47%, 1.3:1 d.r.) as an oil:

7b. IR (film) ν_{max} = 2950, 2870, 1710, 1605, 1450, 1105 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 3.78, 3.35 (maj), 3.67, 3.33 (min), (AB, J= 7.5 Hz, 2H), 3.56, 2.99 (min), 3.53, 3.01 (maj) (AB, J= 8 Hz, 2H), 3.3-3.2 (m, 1H), 2.7-2.55 (m, 2H), 2.2-0.9 (m, 13H), 1.26 (maj), 1.24 (min) (s, 3H), 0.92 (s, 9H), 0.89 (s, 3H), 0.74 (s, 3H); ^{13}C NMR (75.4 MHz, $CDCl_3$) δ 205.8 (C, min), 205.5 (C), 183.5 (C, min),183.2 (C), 132.0 (C), 88.8 (CH, min),88.6 (CH), 83.7 (CH_2), 54.3 (CH, min), 53.5 (CH), 51.7 (CH, min), 51.1 (CH), 50.7 (C), 47.2 (C), 41.7 (CH_2), 41.4 (CH_2, min), 40.6 (CH), 35.3 (CH_2), 35.26 (CH_2, min), 33.39 (CH_2, min), 33.36 (CH_2), 32.8 (C), 29.8 (CH_2), 29.77 (CH_2, min), 28.06 (CH_2), 26.9 (CH_3), 26.8 (CH_2, min), 26.6 (CH_2), 25.5 (CH_2, min), 25.3 (CH_2), 21.7 (CH_3), 21.5 (CH_3, min), 21.2 (CH_3), 12.06 (CH_3, min),.12.03 (CH_3); MS (C.I.-NH_3) m/e = 410 ($M(^{34}S)^+$+18, 6%), 408 (M^++18, 71%), 393 ($M(^{34}S)^+$+1, 9%), 391 (M^++1, 100%), 320 (303+17, 7%), 303 (M^+-87, 22%), 272 (255+17, 19%), 255 ($C_{15}H_{17}SO$, 7%).

General Procedure F. Intermolecular Pauson-Khand Reactions. Thermal Activation.

To a solution of the acetylene thioether **4** (0.32 mmol) in a hydrocarbonated solvent (hexanes or toluene) (5 mL) was added $Co_2(CO)_8$ (0.35 mmol). The formation of a red, dark-colored complex was observed and monitored by TLC. After 30 minutes of stirring at room temperature, the corresponding alkene (3.2 mmol) was added and the reaction mixture was heated at the specified temperature until no dicobalt hexacarbonyl complex could be observed by TLC. The solid suspension was filtered through Celite®, and washed thoroughly with CH_2Cl_2. The combined organic extracts were evaporated *in vacuo*. The crude product was purified by column chromatography on Et_3N pre-treated silica gel (2.5% v/v) eluting with diethyl ether/hexane mixtures of increasing polarity to afford the corresponding cyclopentenone.

General Procedure G. Intermolecular Pauson-Khand Reactions. *N*-Oxide Promoted Reaction.

To a solution of acetylene thioether **4** (0.3 mmol) in CH_2Cl_2 was added $Co_2(CO)_8$ (0.35 mmol). The formation of a red dark colored complex was observed and monitored by TLC. After stirring 30 minutes at room temperature the corresponding alkene (3 mmol) was added and the solution was cooled to -20°C. Then, solid NMO (1.8 mmol) was added. The reaction was stirred until no dicobalt hexacarbonyl complex could be observed by TLC. The solid suspension was filtered through Celite®, and washed thoroughly with CH_2Cl_2. The combined organic extracts were evaporated *in vacuo*. The crude product was purified by column chromatography on Et_3N pre-treated silica gel (2.5% v/v) eluting with diethyl ether/hexane mixtures of increasing polarity to yield the coresponding cyclopentenone.

4-[(1*S*, 2*S*, 4*S*)-1,7,7-Trimethylbicyclo[2.2.1]hept-2-ylsulfanyl]tricyclo [5.2.1.0^{2,6}]deca-4,8-dien-3-one 8a.

The general procedure F (50 °C, 1 h), applied to **4a,** with 2,5-norbornadiene afforded **8a** (56%, 1:1 d.r.) as an oil. The general procedure G (-20 °C, 1 h.), applied to **4a,** with 2,5-norbornadiene afforded **8a** (89%, 1:1 d.r.) as an oil.

8a. IR (film) ν_{max} = 3060, 2940, 2880, 1700, 1560, 1450, 1300, 975, 700 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.96 (a), 6.95 (b), (d, J= 1.5 Hz, 1H), 6.24, 6.16 (ABXY, J= 5.4 Hz, J'= 3 Hz, 2H), 3.2-3.12 (m, 1H), 2.9 (s, 1H), 2.73 (m, 1H), 2.67 (s, 1H), 2.33 (d, J= 4.4 Hz, 1H), 1.95-1.63 (m, 5H), 1.38-1.13 (m, 4H), 0.96 (s, 3H), 0.95 (a), 0.94 (b) (s, 3H), 0.81 (s, 3H); ^{13}C NMR (75.4 MHz, $CDCl_3$) δ 205.9 (C), 152.3 (CH), 147.1 (C), 147.0 (CH*), 138.1 (CH), 136.9 (CH), 52.4 (CH), 51.9 (CH), 51.7 (CH*), 49.5 (C), 48.5 (CH), 47.6 (C), 45.7 (CH), 43.9 (CH), 43.8 (CH*), 43.6 (CH), 41.4 (CH_2), 40.2 (CH_2), 40.02 (CH_2*), 38.4 (CH_2), 27.3 (CH_2), 20.4 (CH_3), 20.1 (CH_3), 13.5 (CH_3), 13.4 (CH_3*).; MS (C.I.-NH_3) m/e = 334 ($M(^{34}S)^+$+18, 9%), 332 (M^++18, 100%), 315 (M^++1, 12%), 154 ($C_{10}H_{17}^+$+17, 3%), 137 ($C_{10}H_{17}^+$, 3%).

4-[(1*S*,2*S*,4*S*)-1,7,7-Trimethylbicyclo[2.2.1]hept-2-ylsulfanyl]tricyclo[5.2.1.$0^{2,6}$]dec-4-en-3-one 9a.

The general procedure F (toluene, 3 days at r.t. and 3 h at 70 °C), applied to **4a,** with norbornene afforded **9a** (74%, 1:1 d.r.) as an oil. The general procedure G (-20 °C, 1 h.), applied to **4a** (0.5 mmol) with norbornene afforded **9a** (79%, 1:1 d.r.) as an oil.

9a. IR (film) ν_{max} = 2940, 2860, 1700, 1560, 1450, 1275, 730 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 6.89 (t, J= 2.7 Hz, 1H), 3.16-3.25 (m, 1H), 2.65 (m, 1H), 2.42 (s, 1H), 2.27 (d, J= 5Hz, 1H), 2.18 (s, 1H), 1.95-0.85 (m, 13H), 1.00 (s, 3H), 0.98 (s, 3H), 0.84 (s, 3H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 207.4 (C), 152.2 (CH), 146.2 (C*), 146.3 (C), 53.8 (CH), 51.9 (CH), 51.7 (CH*), 49.6 (C), 49.3 (CH), 47.7 (C), 45.7 (CH), 40.2 (CH_2), 40.02 (CH_2*),39.3 (CH), 39.2 (CH*), 38.6 (CH), 38.4 (CH_2), 31.2 (CH_2), 28.7 (CH_2), 28.3 (CH_2), 27.3 (CH_2), 20.4 (CH_3), 20.1 (CH_3), 13.5 (CH_3) 13.4 (CH_3*).; MS (C.I.-NH_3) m/e = 336 ($M(^{34}S)^+$+18, 8%), 334 (M^++18, 100%), 317 (M^++1, 14%), 154 ($C_{10}H_{17}^+$+17, 4%), 137 ($C_{10}H_{17}^+$, 4%).

3-[(1*S*, 2*S*, 4*S*)-1,7,7-Trimethylbicyclo[2.2.1]hept-2-ylsulfanyl] bicyclo[3.3.0]oct-3-en-2-one 10a.

The general procedure F (70 °C, 48 h, sealed tube), applied to **4a,** with cyclopentene afforded **10a** (62%, 1:1 d.r.) as an oil. The general procedure G (-20 °C, 3 h.), applied to **4a,** with cyclopentene afforded **10a** (33%, 1:1 d.r.) as an oil.

10a. IR (film) ν_{max} = 2940, 2860, 1700, 1565, 1449, 1278 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.89 (t, J= 2.7 Hz, 1H), 3.3-3.22 (m, 1H), 3.19-3.14 (m, 1H), 2.78 (dd, J= 9.7 Hz, J'=5.7 Hz, 1H), 1.98-1.48 (m, 10H), 1.28-1.11 (m, 3H), 0.96 (s, 3H), 0.93 (s, 3H), 0.79 (s, 3H); ^{13}C NMR (75.4 MHz, $CDCl_3$) δ 209.1 (C), 154.2 (CH), 143.5 (C), 143.4 (C*),51.99 (CH), 51.8 (CH*), 50.2 (CH), 49.6 (C), 47.6 (C), 45.7 (CH), 45.03 (CH), 40.1 (CH_2), 40.02 (CH_2*), 38.4 (CH_2), 30.4 (CH_2), 30.3 (CH_2), 30.2 (CH_2), 27.3 (CH_2), 23.6 (CH_2), 20.4 (CH_3), 20.1 (CH_3), 13.5 (CH_3). 13.4 (CH_3*).; MS (C.I.-NH_3) m/e = 310 ($M(^{34}S)^+$+18, 9%), 308 (M^++18, 100%), 293 ($M(^{34}S)^+$+1, 3%), 291 (M^++1, 38%), 154 ($C_{10}H_{17}^+$+17, 34%), 137 ($C_{10}H_{17}^+$, 96%).

4-[(1*S*,2*R*,3*S*,4*R*)-3-(2,2-Dimethylpropoxy)-4,7,7-trimethylbicyclo[2.2.1]hept-2-ylsulfanyl]tricyclo [5.2.1.$0^{2,6}$]deca-4,8-dien-3-one 8b.

The general procedure F (hexanes, r.t, 24 h), applied to **4b** (0.21 mmol), with 2,5-norbornadiene afforded **8b** (68%, 1:1 d.r.) as an oil. The general procedure G (-20 °C, 16 h.), applied to **4b** (0.21 mmol), with 2,5-norbornadiene afforded **8b** (85%, 1.7:1 d.r.) as an oil.

8b. IR (film) ν_{max} = 3070, 2960, 2880, 1710, 1565, 1475, 1105 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.79 (t, J= 2.4 Hz, 1H), 6.24, 6.19 (ABXY, J= 6 Hz, J'= 3 Hz, 2H), 3.41-3.3 (m, 3H), 3.01 (min), 2.98 (maj) (d, J= 8.1 Hz, 1H), 2.93 (m, 1H), 2.8-2.66 (m, 2H), 2.39-2.33 (m, 1H), 1.81-1.08 (m, 7H), 1.17 (s, 3H), 0.93 (s, 3H), 0.91, 0.89 (s, 9H), 0.78 (s, 3H); ^{13}C NMR (75.4 MHz, $CDCl_3$) δ 205.9 (C), 152.08 (CH, min), 151.75

(CH), 147.7 (C), 138.2 (CH), 136.96 (CH), 88.8 (CH), 88.6 (CH, min), 84.05 (CH_2, min), 84.02 (CH_2), 54.3 (CH), 53.9 (CH, min), 52.6 (CH), 52.5 (CH, min), 50.8 (CH, min), 50.6 (CH), 50.5 (C), 48.5 (CH, min), 48.47 (CH), 47.2 (C), 43.9 (CH), 43.85 (CH, min), 43.7 (CH), 41.45 (CH_2), 33.4 (CH_2), 32.75 (C), 28.35 (CH_2, min) 28.3 (CH_2), 26.9 (CH_3), 21.4 (CH_3), 21.1 (CH_3), 11.9 (CH_3); MS (C.I. -NH_3) m/e = 420 ($M(^{34}S)^+$+18, 9%), 418 (M^++18, 100%), 403 ($M(^{34}S)^+$+1, 2%), 401 (M^++1, 19%), 313 (M+-87, 9%).

4-[(1*S*,2*R*,3*S*,4*R*)-3-(2,2-Dimethylpropoxy)-4,7,7-trimethylbicyclo[2.2.1]hept-2-ylsulfanyl]tricyclo [5.2.1.0^{2,6}]dec-4-en-3-one 9b.

The general procedure F (hexanes, r.t., 26 h), applied to **4b** (0.21 mmol), with norbornene afforded **9b** (81%, 1.5:1 d.r.) as an oil. The general procedure G (-20 °C, 7 h.), applied to **4b** (0.21 mmol), with norbornene afforded **9b** (98%, 1:1.6 d.r.) as an oil.

9b. IR (film) ν_{max} = 2960, 2870, 1705, 1565, 1475, 1105 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.71 (m, 1H), 3.4-3.3 (m, 3H), 3.0 (min), 2.96 (maj) (d, J= 7.8 Hz, 1H), 2.65-2.15 (m, 4H), 1.8-1.17 (m, 10H), 1.16 (s, 3H), 1.08-1.04 (m, 1H), 0.92 (s, 3H), 0.90 (min), 0.89 (maj) (s, 9H), 0.77 (s, 3H); ^{13}C NMR (75.4 MHz, $CDCl_3$) δ 207.3 (C), 151.8 (CH), 146.8 (C), 88.8 (CH, min), 88.6 (CH), 84.06 (CH_2), 84.02 (CH_2, min), 54.4 (CH, min), 54.1 (CH), 53.97 (CH, min), 53.9 (CH), 50.8 (CH), 50.6 (CH, min), 50.5 (C), 49.25 (CH), 49.22 (CH, min), 47.2 (C), 39.3 (CH), 38.7 (CH), 33.4 (CH_2), 32.8 (C), 31.3 (CH_2), 28.8 (CH_2), 26.9 (CH_3), 21.5 (CH_3), 21.1 (CH_3), 11.9 (CH_3).; MS (C.I.-NH_3) m/e = 422 ($M(^{34}S)^+$+18, 9%), 420 (M^++18, 100%), 405 ($M(^{34}S)^+$+1, 2%), 403 (M^++1, 26%), 315 (M^+-87, 12%).

3-[(1*S*,2*R*,3*S*,4*R*)-3-(2,2-Dimethylpropoxy)-4,7,7-trimethylbicyclo[2.2.1]hept-2-ylsulfanyl]bicyclo [3.3.0]oct-3-en-2-one 10b.

The general procedure F (80 °C, 48 h, sealed tube), applied to **4b** (0.21 mmol), with cyclopentene (after 24 h additional 0.18 mL were added) afforded **10b** (58%, 2.2:1 d.r.) as an oil. The general procedure G (-20 °C, 28 h.), applied to **4a** (0.21 mmol), with cyclopentene (after 24h an additional amount of NMO (1.3 mmol) was added) afforded **10b** (48%, 4.6:1 d.r.) as an oil.

10b. IR (film) ν_{max} = 2950, 2860, 1710, 1570, 1475, 1115 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.75 (m, 1H), 3.40, 3.35 (AB, J= 7.6 Hz, 2H), 3.33, 3.01 (AB, J= 7.8 Hz, 2H), 1.99-1.2 (m, 10H), 1.17 (s, 3H), 1.07-0.95 (m, 1H), 0.93 (s, 3H), 0.91, 0.90 (s, 9H), 0.78 (s, 3H); ^{13}C NMR (75.4 MHz, $CDCl_3$) δ 209.07 (C), 153.8 (CH), 153.6 (CH, min), 143.97 (C), 88.7 (CH, min), 88.6 (CH), 84.07 (CH_2), 84.04 (CH_2, min), 54.3 (CH, min), 54.1 (CH), 50.7 (CH), 50.6 (CH, min), 50.5 (C), 50.31 (CH, min), 50.3 (CH), 47.2 (C), 45.07 (CH), 33.4 (CH_2), 32.8 (C), 30.4 (CH_2, min), 30.3 (CH_2), 28.4 (CH_2), 26.9 (CH_3), 23.7 (CH_2), 21.5 (CH_3), 21.1 (CH_3), 11.9 (CH_3); MS (C.I. -NH_3) m/e = 396 ($M(^{34}S)^+$+18, 9%), 394 (M^++18, 100%), 379 ($M(^{34}S)^+$+1, 2%), 377 (M^++1, 24%), 289 (M^+-87, 15%).

4-Pentyl-5-[(1*S*,2*S*,4*S*)-1,7,7-trimethylbicyclo[2.2.1]hept-2-ylsulfanyl]tricyclo[5.2.1.0^{2,6}]deca-4,8-dien-3-one 11a.

The general procedure F (hexanes, 70°C, 3 h), applied to **5a** (0.15 mmol), with 2,5-norbornadiene afforded **11a** (56%, 1:1 d.r.) as an oil. The general procedure G (0 °C, 12 h.), applied to **5a** (0.23 mmol), with 2,5-norbornadiene afforded **11a** (53%, 1:1 d.r.) as an oil.

IR (film) ν = 3040, 2930, 2850, 1695, 1570, 1450, 700 cm^{-1}. ^1H-NMR (200 MHz, $CDCl_3$) δ 6.25-6.24 (m, 1H), 3.6-3.4 (m, 1H), 2.94 (s, 1H), 2.9-1 (m, 23H), 2.79 (s, 1H), 1.03 (a), 1.01 (b) (s, 3H), 0.97 (a), 0.95 (b) (s,

3H), 0.81 (s, 3H). ^{13}C-NMR (50 MHz, $CDCl_3$) d = 206.26 (C), 206.16 (C*), 180.9 (C), 180.8 (C*), 139.2 (C), 138.8 (C*), 137.85 (CH*), 137.77 (CH), 137.5 (CH), 137.42 (CH*), 52.5 (CH), 52.2 (CH*), 52.0 (CH), 49.9 (CH*), 49.6 (CH), 49.3 (C), 47.5 (C), 45.9 (CH), 43.7 (CH), 42.8 (CH*), 42.7 (CH), 41.5 (CH_2), 40.4 (CH_2), 37.9 (CH_2), 31.96 (CH_2*), 31.85 (CH_2), 31.03 (CH_2*), 30.9 (CH_2), 27.4 (CH_2), 27.15 (CH_2), 22.4 (CH_2), 20.5 (CH_3), 20.3 (CH_3), 13.9 (CH_3), 13.8 (CH_3), 13.7 (CH_3*). MS (C.I.-NH_3) m/e = 402 (M^++18, 8%), 387 ($M(^{34}S)^+$+1, 10%), 385 (M^++1, 100%), 266 (249+17, 14%), 249 (M^+-135, 36%), 154 ($C_{10}H_{17}^+$+17, 4%), 137 ($C_{10}H_{17}^+$, 11%).

4-Butyl-5-[(1*S*,2*R*,3*S*,4*R*)-3-(2,2-dimethylpropoxy)-4,7,7-trimethylbicyclo[2.2.1]hept-2-ylsulfanyl] tricyclo[5.2.1.0^{2,6}]deca-4,8-dien-3-one 11b.

The general procedure F (hexanes, 70°C, 22 h), applied to **5a** (0.18 mmol), with 2,5-norbornadiene afforded **11b** (56%, 2.1:1 d.r.) as an oil. The general procedure G (-20 °C, 48 h.; after 24h an additional amount of NMO (1.3 mmol) was added), applied to **5a** (0.18 mmol), with 2,5-norbornadiene afforded **11b** (58%, 4.1:1 d.r.) as an oil.

IR (film) ν = 2960, 2880, 1700, 1580, 1460, 1110, 710 cm^{-1}. ^{1}H-NMR (200 MHz, $CDCl_3$) δ 6.22 (m, 2H), 3.96-2.2 (m, 10H), 1.7-1 (m, 11H), 0.96-0.73 (m, 6H), 1.25 (s, 3H), 0.92 (s, 9H), 0.73 (s, 3H). ^{13}C-NMR (75 MHz, $CDCl_3$) δ 206.2 (C), 182.25 (C), 182.15 (C, min), 138.9 (C), 137.83 (CH, min), 137.8 (CH), 137.49 (CH, min), 137.35 (CH), 88.7 (CH), 83.7 (CH_2), 54.2 (CH, min), 53.06 (CH), 52.2 (CH, min), 51.9 (CH), 51.3 (CH), 50.7 (C), 50.1 (CH), 49.8 (CH, min), 47.2 (C), 43.9 (CH), 43.6 (CH, min), 42.8 (CH), 42.6 (CH, min), 41.4 (CH_2), 33.3 (CH_2), 32.8 (C), 30.83 (CH_2), 30.78 (CH_2, min), 29.89 (CH_2, min),29.77 (CH_2), 28.01 (CH_2), 26.9 (CH_3), 27.8 (CH_2, min), 23.04 (CH_2), 22.84 (CH_2, min), 21.7 (CH_3), 21.6 (CH_3, min), 21.3 (CH_3, min), 21.2 (CH_3), 13.9 (CH_3), 13.8 (CH_3, min), 12.03 (CH_3). MS (C.I.-NH_3) m/e = 476 ($M(^{34}S)^+$+18, 2%), 474 (M^++18, 20%), 459 ($M(^{34}S)^+$+1, 10%), 457 (M^++1, 100%), 369 (M^+-87, 10%).

REFERENCES AND NOTES

1.- For recent reviews on the Pauson-Khand reaction, see: (a) Harrington, P. J. *Transition Metals in Total Synthesis*; Wiley: New York, 1990, pp. 259-301. (b) Schore, N. E. *Org. React.* **1991**,*40*, 1-90. (c) Schore, N. E. in *Comprehensive Organic Synthesis*; Trost, B. M. Ed.; Pergamon Press: Oxford, 1991; vol. 5, pp. 1037-1064. (d) Schore, N. E. in *Comprehensive Organometallic Chemistry II*; Hegedus, L. S. Ed.; Elsevier: Oxford, 1995; vol. 12, pp. 703-739.

2.- (a) Bladon, P.; Pauson, P. L.; Brunner, H.; Eder, J. *J. Organomet. Chem.* **1988**, *353*, 449-454. (b) Brunner, H.; Niederhuber, A. *Tetrahedron: Asymmetry* **1990**, *1*, 711-714. (c) Park, H.-J.; Lee, B. Y.; Kang, Y. K.; Chung, Y. K. *Organometallics* **1995**, *14*, 3104-3107. (d) Hay, A. M.; Kerr, W. J.; Kirk, G. G.; Middlemiss, D. *Organometallics* **1995**, *14*, 4986-4988. (e) Kerr, W.J.; Kirk, G.G.; Middlemiss, D. *Synlett* **1995**, 1085-1086.

3.- For asymmetric versions of Pauson-Khand type reactions with other metals see: Hicks, F.A.; Buchwald, S.L. *J. Am. Chem. Soc.* **1996**, *118*, 11688-11689.

4.- (a) Castro, J.; Sörensen, H.; Riera, A.; Morin, C.; Moyano, A.; Pericàs, M. A.; Greene, A. E. *J. Am. Chem. Soc.* **1990**, *112*, 9388-9389. (b) Verdaguer, X.; Moyano, A.; Pericàs, M. A.; Riera, A.; Greene, A. E.; Piniella, J.; Alvarez-Larena, A. *J. Organomet. Chem.* **1992**, *433*, 305-310. (c) Castro, J.; Moyano, A.; Pericàs, M. A.; Riera, A.; Greene, A. E. *Tetrahedron: Asymmetry* **1994**, *5*, 307-310.

5.- (a) Poch, M.; Valentí, E.; Moyano, A.; Pericàs, M. A.; Castro, J.; De Nicola, A.; Greene, A. E. *Tetrahedron Lett.* **1990**, *31*, 7505-7508. (b) Bernardes, V.; Verdaguer, X.; Kardos, N.; Riera, A.; Moyano, A.; Pericàs, M. A.; Greene, A. E. *Tetrahedron Lett.* **1994**, *35*, 575-578. (c) Verdaguer, X.; Moyano, A.; Pericàs, M. A.; Riera, A.; Bernardes, V.; Greene, A. E.; Alvarez-Larena, A.; Piniella, J. F. *J. Am. Chem. Soc.* **1994**, *116*, 2153-2154.

6.- Castro, J.; Moyano, A.; Pericàs, M. A.; Riera, A.; Greene, A. E.; Piniella, J.; Alvarez-Larena, A. *J. Org. Chem.* **1996**, *61*, 9016-9020.

7.- Bernardes, V.; Kann, N.; Riera, A.; Moyano, A.; Pericàs, M. A.; Greene, A. E. *J. Org. Chem.* **1995**, *60*, 6670-6671.

8.- Tormo, J.; Moyano, A.; Pericàs, M.A.; Riera, A. submitted for publication

9.- For a review on preparation of acetylene thioethers: Brandsma, L; Bos, H.J.T.; Arens, J.F. in *Chemistry of Acetylenes*; Viehe, H. G. Ed.; Marcel Dekker:New York, 1969; Chapter 11.

10.- (a) Cookson, R.C.; Gopalan, R. *J. Chem. Soc. Chem. Commun.* **1978**, 924-925. (b) Isobe, M.; Nishikawa, T.; Herunsalee, A.; Tsukiyama, T.; Hirose, Y.; Shimokawa, K.; Goto, T. *Pure & Appl. Chem.* **1990**, *62*, 2007. (c) Hunter, G.A.; McNab, H. *Synthesis* **1993**, 1067-1068. (d) Magriotis, P.A.; Brown, J.T. *Org. Synth.* **1993**, *72*, 252-261 and references therein.

11.- Bernardes, V.; Verdaguer, X.; Moyano, A.; Pericàs, M. A.; Riera, A.; Greene, A. E. *J. Organomet. Chem.* **1994**, *470*, C12-C14.

12.- Nebois, P.; Kann, N.; Greene, A.E. *J. Org. Chem.* **1995**, *60*, 7690-7692.

13.- (a) Zilverschoon, A.; Meijer, J.; Vermeer, P.; Brandsma, L. *Recl. Trav. Chim. Pays-Bas* **1974**, *94*, 163-165. (b)Verboom, W.; Schoufs, M.; Meijer, J.; Verkruijsse, H.D. ; Brandsma, L. *Recl. Trav. Chim. Pays-Bas* **1978**, *97*, 244-246. (c) Sukhai, R.S.; Verboom, W.; Meijer, J.; Schoufs, M.J.M.; Brandsma, L. *Recl. Trav. Chim. Pays-Bas* **1981**, *100*, 10-13. (d) Carlson, R.M.; Isidor, J.L. *Tetrahedron Lett.* **1973**, *48*, 4819-4822. (e) Miyachi, N.; Shibasaki, M. *J. Org. Chem.* **1990**, *55*, 1975. (e) Kabanyane, S.T.; MaGee, D.I. *Can. J. Chem.* **1992**, *70*, 2758-2763.

14.- (a) Miller, S.I.; Orzech, C.E.; Welch, C.A.; Ziegler, G.R. Dickstein, J.I. *J. Am. Chem. Soc.* **1962**, *84*, 2020-2021. (b) Fischer, D.R.; Williamson, B.L.; Stang, P.J. *Synlett*, **1992**, 535-536. (c) Stang, P.J.; Zhdankin, V.V. *J. Am. Chem. Soc.* **1991**, *113*, 4571-4576.

15.- Raap, R.; Micetich, R.G. *Can. J. Chem.* **1968**, *46*, 1057-1063.

16.- Everhardus, R.H.; Brandsma, L. *Synthesis*, **1978**, 359.

17.- Blanco, J.M.; Caamaño, O.; Eirín, A.; Fernández, F.; Medina, L. *Synthesis*, **1990**, 584-586.

18.- Lee, D.-S; Hung, S.-M.; Lai, M.-C.; Chu, H.-Y.; Yang *Org. Prep.. Proc. Int.* **1993**, *25*, 673-679.

19.- Oppolzer, W.; Chapuis, C.; Dupuis, D.; Guo, M. *Helv. Chim. Acta.* **1985**, *68*, 2100-2114.

20.- (a) Shambagati, P.S.; Crowe, W.E.; Schreiber, S.L. *Tetrahedron Lett.* **1990**, *31*, 5289-5292. (b) Jeong, N.; Chung, Y.K; Lee. B.Y.; Lee, S.H.; Yoo, S.-E. *Synlett* **1991**, 204-206.

21.- Daalman, L.; Newton, R.F.; Pauson, P.L.; Wadsworth, A. *J. Chem. Res.(S)* **1984**, 346-347.

22.- Moyano, A.; Pericàs, M. A.; Riera, A.; Greene, A.E. unpublished results.

(*Received in UK* 24 *March* 1997; *revised* 14 *May* 1997; *accepted* 15 *May* 1997)