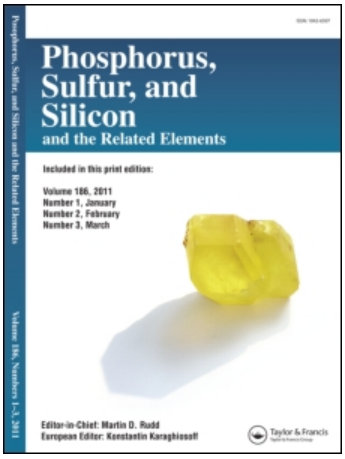

Phosphorus, Sulfur, and Silicon and the Related Elements
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713618290

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To cite this Article Levsen, Steven M. , Peterson, Andrew C. and Cremer, Sheldon E.(1997) 'STEREOSELECTIVE PREPARATION OF THE *ENDO*-2-PHOSPHORUS SUBSTITUTEd BICYCLO[2.2.1]HEPTANE SYSTEM', Phosphorus, Sulfur, and Silicon and the Related Elements, 123: 1, 35 — 44
To link to this Article: DOI: 10.1080/10426509708044196
URL: http://dx.doi.org/10.1080/10426509708044196

Phosphorus, Sulfur, and Silicon, 1997, Vol. 123, pp. 35-44
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STEREOSELECTIVE PREPARATION OF THE *ENDO*-2-PHOSPHORUS SUBSTITUTED BICYCLO[2.2.1]HEPTANE SYSTEM*

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(Received 11 August 1996; In final form 22 October 1996)

The secondary phosphonate ester *endo*-2-(diethoxyphosphoryl)bicyclo[2.2.1]heptane **6** was prepared in stereoselective fashion for the first time by hydrogenation of 2-(diethoxyphosphoryl)bicyclo[2.2.1]hept-2-ene **1.** The precursor vinylphosphonate **1** was prepared by two different routes. Of these, the direct preparation of phosphonate **6** from norbornene in 76 % overall yield proved to be the most convenient. Treatment of **6** with PCl_5 at 105 °C gave exclusively endo dichloride **7**. This same reaction at 120-140 °C gave a 3:1 ratio of endo- to exo-phosphonic dichlorides **7** and **8**, respectively. When pure **7** or **8** were exposed to PCl_5 at 120-140 °C isomerization of each occurred.

Keywords: Bicyclo[2.2.1]heptane; bicyclo[2.2.1]hept-2-ene; norbornyl; norbornenyl; phosphonate; stereoselective; isomerization

INTRODUCTION

Considerable progress has been made towards the stereoselective construction of both cyclic and acyclic organophosphorus compounds which contain chiral phosphorus or carbon centers. Several interesting new approaches have been developed to extend traditional synthetic and derivatization methods into this realm.[1] In addition, it has proven advantageous in several recent studies to adapt popular chiral reagents for the stereoselective synthesis of specific asymmetric organophosphorus compounds.[2] These studies have greatly augmented the traditional methods for the stereoselective synthesis of organophosphorus compounds which have been discussed in several excellent reviews.[3] Phosphorus compounds which contain chiral centers have been employed as ligands in conjunc-

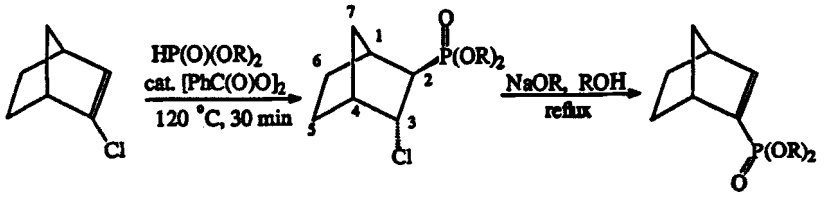
* Dedicated to Professor Robert Wolf on the occasion of his 70th birthday.

tion with asymmetric transition metal catalysis[4] and have been used to induce asymmetry into nearby prochiral centers.[5] The preparation of biologically important organophosphorus compounds has provided impetus for their construction.[6]

Our previous paper on this subject described the stereoselective synthesis and subsequent transformations of *exo*-2-phosphoryl substituted bicyclo[2.2.1]heptanes (norbornanes).[7] This investigation revealed that (+/–)-*exo*-2-(dimethoxyphosphoryl)bicyclo[2.2.1]heptane and (+/–)-*exo*-2-(diethoxyphosphoryl) bicyclo[2.2.1]heptane were cleanly converted into (+/–)-*exo*-2-(dichlorophosphoryl)bicyclo[2.2.1]heptane upon treatment with two equivalents of PCl_5 at 105 °C for 16 h. Isomerization at the α-carbon of the *exo*-2-phosphoryl substituted norbornanes was observed only in a few instances despite the relatively harsh conditions necessary for derivatization. It was also of interest to gain entry into the corresponding *endo*-2-phosphoryl substituted bicyclo[2.2.1]heptane system via a facile, stereoselective approach. Once accomplished, the goal was to probe the ease of derivatization and the α-C-H lability in this endocyclic system. Previous synthesis of *endo*-dialkylphosphonates were not stereoselective[8]; instead, exo/endo phosphonate mixtures (~50:50) were produced which required separation. Mixtures of the *exo/endo*-2-(dialkoxyphosphoryl)bicyclo[2.2.1]hept-5-ene analogs of **6** have been previously prepared by the Diels-Alder reaction of cyclopentadiene with dimethyl vinyl phosphonate (45 % yield)[8b] and diethyl vinyl phosphonate (76 % yield)[8a]. This report describes the stereoselective synthesis of the *endo*-2-phosphoryl substituted bicyclo[2.2.1]heptane **6** and conversion to the *endo*-dichloride **7**.

RESULTS AND DISCUSSION

Two methods were employed to prepare *endo*-2-(dialkoxyphosphoryl)heptanes from readily available starting materials. Both methods required the formation of the vinyl phosphonate **1** which could then be hydrogenated exclusively at the exo face to give endo phosphonate. The addition of dimethyl phosphite to 2-chlorobicyclo[2.2.1]hept-2-ene[9] under free radical conditions at 120 °C gave β-chlorophosphonate **2** in 64 % isolated yield (Scheme 1). In a similar manner, diethyl phosphite addition to 2-chlorobicyclo[2.2.1]hept-2-ene produced β-chlorophosphonate **3** in 42 % yield. Unlike the addition of these dialkyl phosphites to norbornene,[8b] the reaction of these dialkyl phosphites to 2-chloronorbornene was not self-sustaining. Consequently, it was necessary to add the dibenzoyl peroxide initiator sequentially in several portions. Moreover, the addition of the dialkyl phosphite radical still proceeded at the exo face of 2-chlorobicyclo[2.2.1]heptene



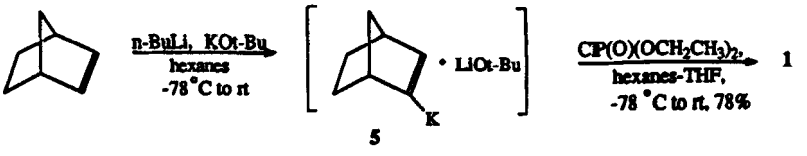
2 R = CH_3 (64%) **4** R = CH_3 (26%)

3 R = CH_2CH_3 (42%) **1** R = CH_2CH_3 (76%)

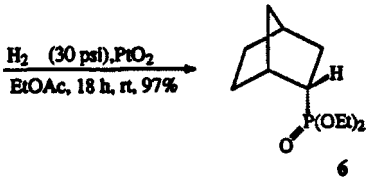
SCHEME 1

to give the *exo*-phosphonates **2** and **3** stereoselectively. The stereochemical assignments for phosphonates **2** and **3** were determined from their ^1H NMR and COSY spectra. Treatment of **2** and **3** with NaOMe or NaOEt, respectively, gave **4** and **1**.

A second route to **1** was developed. The active Lochmann-Schlosser base couple, formed by the *in situ* treatment of n-butyllithium with potassium t-butoxide,[10] was used to deprotonate norbornene to give the vinyl-potassium ion pair **5** (Scheme 2). The vinyl anion intermediate **5** was then treated with chlorodiethylphosphonate to give **1** in 78 % yield.



5

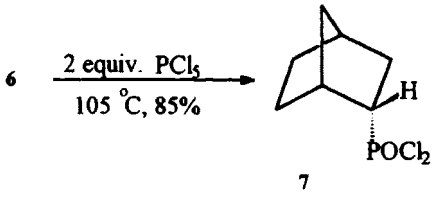


6

SCHEME 2

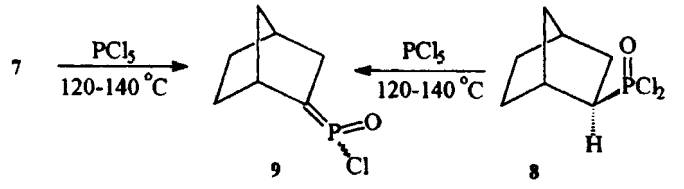
With the vinylphosphonate **1** in-hand, the title phosphonate **6** was prepared in nearly quantitative yield from vinylphosphonate **1** via reduction of the olefinic bond with PtO_2 under 30 psi of hydrogen. As expected,[11] the reduction of vinylphosphonate **1** was completely selective as the isomeric (+/–)-*exo*-2-(diethoxyphosphoryl)bicyclo[2.2.1]heptane was not observed by mass spectrometry or by NMR spectroscopy.

It was of interest to compare the potential for isomerization of the *endo*-phosphonate **6** with the exocyclic counterpart. We previously reported[7] that treatment of *(+/–)-exo*-2-(diethoxyphosphoryl)bicyclo[2.2.1]heptane with two eq. of phosphorus pentachloride gave only the *exo*-dichloride **8.** In this study, treatment of *endo*-phosphonate **6** under similar conditions produced exclusively *endo*-dichloride **7** (eq 1).



(1)

However, when the same reaction was run at 120-140 °C for 16 h, with a 5 mmol excess of PCl_5, a 3:1 mixture of endo: exo dichlorides **7** and **8** resulted. When pure **7** or **8** were exposed to PCl_5 at elevated temperatures isomerization occurred (eq 2).



(2)

The isomerization presumably occurred by thermal elimination of HCl to give intermediate **9**, followed by protonation at either the exo or endo face and addition of chloride ion to produce **7** and **8**. Heating neat **7**, or **7** with 0.2 eq. of phosphorus oxychloride at 140 °C for 4 h did not result in isomerization. This control experiment suggests that PCl_5 is an essential component for the isomerization process.

The reliable and comprehensive ^{13}C NMR spectral correlations of Quin and coworkers were utilized to establish the endocyclic versus exocyclic configuration of the phosphorus substituents in the current investigation.[12] In addition, the ^{1}H and ^{13}C NMR spectral assignments for vinylphosphonate **1** and **4** and *endo*-phosphonate **6** were established using the combined results from 1D, 2D-COSY and HETCOR experiments.

One additional method to prepare vinyl phosphonate **1** was attempted. The readily available 2-(diethoxyphosphoryl)-2-hydroxybicyclo[2.2.1]heptane [8d, 8e]

was treated with dehydration reagents($SOCl_2$/pyridine, I_2, H_2SO_4, polyphosphoric acid) with limited success. A complex mixture of products resulted.

The short route (Scheme 2) to *endo*-phosphonate **6** from norbornene in 76 % overall yield provides a convenient, multigram synthetic method which avoids chromatography. Complete stereoselectivity to form **6** was achieved using this approach. Further investigations into the synthesis of prochiral, asymmetric phosphorus compounds and their subsequent transformations are in progress.

EXPERIMENTAL

Proton NMR spectra were recorded on a Varian 360L or GE Omega 300NB spectrometer. Chemical shifts are reported on the delta scale from internal TMS. Both ^{13}C and ^{31}P NMR spectra were recorded with proton decoupling on a JOEL JNM-FX60Q or a GE OMEGA 300NB spectrometer. Chemical shifts for ^{13}C NMR spectra are reported from internal TMS. Coupling constants (J_{PC}) are reported in Hz in parentheses. Chemical shifts for ^{31}P NMR spectra are reported in parts per million downfield from external 85 % H_3PO_4. GC-MS results were obtained from a Hewlett-Packard model 5970 spectrometer at 70 eV using a 0.25 mm × 30 m DB-1 capillary column. IR spectra were recorded on an Analect Instruments FX 6200 FTIR spectrometer. Elemental Analyses were performed by Midwest Microlab, LTD., Indianapolis, Indiana. High Resolution mass spectrometry (EI and FAB) were conducted by the Midwest Center for Mass Spectrometry [partial support by the National Science Foundation, Biology Division (Grant No. DIR9017262)]. All boiling and melting points (Thomas-Hoover apparatus) are uncorrected. Reactions, unless otherwise noted, were conducted under a nitrogen atmosphere. Moisture sensitive compounds and reagents were handled in a Labconco glovebox. Diethyl ether and THF were distilled from sodium or potassium/benzophenone ketyl. All reagents were obtained from Aldrich Chemical Co. and used as received unless otherwise noted. Diethyl phosphite was obtained from Eastman Kodak. The ^{31}P NMR spectra were utilized primarily to insure the purity of the products. In addition, the sensitivity of ^{31}P NMR spectroscopy greatly assisted in the observance of traces of isomers or phosphorus-containing by-products. All product ratios were determined by integration of the ^{31}P NMR spectral resonances obtained from experiments conducted with pre-delay values five times the expected relaxation time.[13] A ^{31}P NMR spectrum was also taken of the crude reaction mixtures to insure the integrity of isomer ratios.

(+/–)-2-Chlorobicyclo[2.2.1]hept-2-ene

Prepared by the method of McDonald and Steppel[9] in 89 % yield after distillation through a 4 cm Vigreux column: bp 64 °C (55 mm), lit[9] bp 62-63 °C (57 mm); ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.79 (d, J = 3.3 Hz, 1 H), 2.95-2.78 (m, 1 H), 2.85-2.59 (m, 1 H), 1.77-1.63 (m, 2 H), 1.62-1.55 (m, 1 H), 1.32-1.09 (m, 3 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 137.54, 129.91, 48.87, 47.95, 43.04, 26.23, 24.37.

***(+/–)-endo-3-Chloro-exo-2-(dimethoxyphosphoryl)bicyclo[2.2.1]heptane* 2**

A mixture of 2-chlorobicyclo[2.2.1]hept-2-ene (10 g, 77 mmol), dimethyl phosphite (16.9 g, 0.15 mol) and benzoyl peroxide (0.25 g) in an 18 × 2 cm pressure tube (capped with a Teflon screw cap) was partially immersed into a 170 °C oil bath for 8 h. Additional benzoyl peroxide (~0.1 g) was added after 2,4, and 6 h. The excess starting materials were removed by distillation (bp 25-50 °C, 20 mm). The crude product which remained was distilled (bp 85-86 °C, 0.2 mm) to give 13.1 g of phosphonate which contained 10 % dimethylphosphite (^{31}P NMR spectroscopy). This product mixture was added to ether (250 mL) and then washed with 5 % NaOH (3 × 100 mL), H_2O (100 mL) and brine (100 mL). The ethereal layer was dried over $MgSO_4$ and concentrated *in vacuo*. Molecular distillation (90 °C, 0.1 mm) furnished the analytical sample of phosphonate **2**: 11.8 g (64 %); ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.35 (m, 1 H, H-3), 3.76 (d, J = 10.7 Hz, 3 H, OMe), 3.75 (d, J = 10.7 Hz, 3 H, OMe), 2.57-2.49 (m, 1 H, H-1), 2.48-2.42 (m, 1 H, H-4), 2.04-1.92 (m, 1 H), 1.84-1.33 (m, 6 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 59.93 (d, J = 3.7, C-3), 52.43 (d, J = 6.7, OCH_3), 52.30 (d, J = 6.7, OCH_3), 48.22 (d, J = 142.2, C-2), 43.43 (d, J = 5.5, C-4), 38.78 (C-1), 36.25 (C-7), 30.91 (d, J = 16.5, C-6), 21.16 (C-5); ^{31}P NMR (121 MHz, $CDCl_3$) δ 32.1; GCMS: m/e (%), 240 (M^+, 5), 238 (M^+, 13), 209 (76), 211 (24), 203 (100). Anal. Calcd for $C_9H_{16}ClO_3P$: C, 45.30; H, 6.76. Found: C, 45.32; H, 6.72.

***(+/–)-endo-3-Chloro-exo-2-(diethoxyphosphoryl)bicyclo[2.2.1]heptane* 3**

A mixture of 2-chlorobicyclo[2.2.1]hept-2-ene (4.0 g, 31 mmol), diethyl phosphite (8.6 g, 62 mmol) and benzoyl peroxide (0.1 g) in a 10 × 2 cm pressure tube (Ace Glass, Inc; model no. 5848-07) was sealed with a Teflon screw cap and partially immersed into a 170 °C oil bath for 8 h. Additional benzoyl peroxide (~0.1 g) was added after 2,4, and 6 h. The excess starting materials were removed by distillation (bp 30 °C, 20 mm). The crude product was distilled (bp 86-92 °C, 0.05-0.07 mm) to give 4.1 g of a clear, colorless liquid which contained 10 %

diethyl phosphite (^{31}P NMR spectroscopy). This product mixture was dissolved in ether (25 mL). The ethereal solution was washed with 5 % NaOH (3 X 10 mL), H_2O (10 mL) and brine (10 mL). The organic layer was then dried with $MgSO_4$ and concentrated *in vacuo*.Phosphonate **3** was further purified by molecular distillation (40-50 °C, 0.1 mm): 3.55 g (42 %); ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.32 (m, 1 H, H-3), 4.18-3.97 (m, 4 H, OCH_2), 2.53-2.42 (m, 1 H, H-1), 2.45-2.38 (m, 1 H, H-4), 2.02-1.90 (m, 1 H), 1.84-1.23 (m, 6 H), 1.28 (t, J = 7.1 Hz, 6 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 61.76 (d, J = 5.5, OCH_2) and 61.67 (d, J = 5.5, OCH_2), 60.17 (d, J = 3.7, C-3), 48.71 (d, J = 142.8, C-2), 43.54 (d, J = 5.5, C-4), 38.85 (C-1), 36.30 (C-7), 31.02 (d, J = 16.5, C-6), 21.32 (C-5), 16.17 (d, J = 6.1, CH_3); ^{31}P NMR (121 MHz, $CDCl_3$) δ 29.5. Anal. Calcd for $C_{11}H_{20}ClO_3P$; C, 49.54; H, 7.56. Found: C, 49.75; H, 7.32.

(+/–)-2-(Dimethoxyphosphoryl)bicyclo[2.2.1]hept-2-ene **4**

Sodium metal (0.29 g, 13 mmol) was added to anhydrous methanol (45 mL) in one portion at room temperature. After all of the sodium metal reacted, a solution of phosphonate **2** (2.0 g, 8.4 mmol) in methanol (5 mL) was added in one portion at rt. The reaction mixture was then heated at reflux for 16 h, cooled to rt, and concentrated *in vacuo*. Ether (60 mL) was added and the resultant ethereal solution was washed with H_2O (20 mL) and brine (3 × 20 mL), dried over $MgSO_4$and concentrated *in vacuo*. Molecular distillation (50 °C, 0.1 mm) provided purified vinylphosphonate **4** (0.44 g, 26 %). ^{31}P NMR (121 MHz, $CDCl_3$) δ 19.81. GC-MS: m/e (%), 202 (M^+, 4), 174 (100), 173 (22), 155 (3), 142 (14), 109 (40), 96 (20), 91 (23), 79 (70), 78 (22), 77 (13), 65 (35).

(+/–)-2-Diethoxyphosphoryl)bicyclo[2.2.1]hept-2-ene **1**

Sodium metal (1.29 g, 56 mmol) was added to absolute ethanol (250 mL) at rt. The resultant mixture was stirred at room temperature until the solid sodium metal reacted completely and hydrogen gas no longer evolved. Then, 3-chlorophosphonate **3** (10.0 g, 38 mmol) was added to the sodium ethoxide solution at room temperature. The reaction mixture was heated at reflux for 6 h. A white solid gradually precipitated. The reaction mixture was cooled to room temperature, concentrated *in vacuo* and added to ether (300 mL). The ethereal solution was filtered, washed with H_2O (100 mL) and then washed with brine (3 × 100 mL). The organic layer was separated, dried with $MgSO_4$, and concentrated *in vacuo*. Short path distillation gave **1** as a clear, colorless liquid: bp 115-125 °C, 0.5 mm; 6.56 g (76 %); ^{1}H NMR (60 MHz, $CDCl_3$) δ 6.81 (dd, J_{HH} = 3.2 Hz,

J_{PH} = 11.3 Hz, 1 H, H-3), 4.06-3.88 (m, 4 H, OCH_2), 3.10-3.04 (m, 1 H, H-1), 2.97-2.91 (m, 1 H, H-4), 1.72-1.57 (m, 2 H), 1.43-1.37 (m, 1 H), 1.23 (t, J = 7.0 Hz, 3 H, Me), 1.22 (t, J = 7.1 Hz, 3 H, Me), 1.19-1.12 (m, 1 H), 1.12-0.91 (m, 2 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 151.19 (d, J = 10.4, C-3), 136.32 (d, J = 194.7, C-2), 61.29 (d, J = 5.5, OCH_2) and 61.27 (d, J = 5.5, OCH_2), 48.92 (d, J = 7.3, C-7), 43.38 (C-1), 43.29 (d, J = 4.3, C-4), 24.30 (C-5), 24.08 (d, J = 3.7, C-6), 16.18 (d, J = 6.1, CH_3); ^{31}P NMR (121 MHz, $CDCl_3$) δ 17.3; GC-MS: m/e (%); 230 (M^+, 3), 202 (59), 174 (20), 158 (20), 146 (68), 129 (19), 128 (21), 110 (33), 109 (34), 92 (62), 91 (62), 66 (100). HRMS Calcd for $C_{11}H_{19}O_3P$: 230.1072. Found: 230.1067.

Alternative Method: Potassium *t*-butoxide (2.5 g, 22 mmol) was added to a 1.5 M solution of *n*-butyllithium in hexanes at -78 °C under N_2 in small portions over a 30 min period. The resultant heterogeneous mixture (Lochmann-Schlosser base solution [10]) was stirred at -78 °C for 10 min. Then, a solution of norbornene (2.0 g, 21 mmol) in pentane (15 mL) was added to the Lochmann-Schlosser base solution at -78 °C dropwise over a 45 min period. The resultant reaction mixture was warmed to room temperature over a 2 h period and stirred at room temperature for 48 h. The reaction mixture, which contained a brown suspension, was cooled to -78 °C. A solution of diethyl chlorophosphate (4.1 mL, 28 mmol) was added dropwise to the cooled (-78 °C) Lochmann-Schlosser base solution over a 1 h period. The resultant reaction mixture was warmed to room temperature over a 2 h period, stirred for 24 h, then added to *sat'd* NH_4Cl (20 mL) and then added to ether (50 mL). The organic layer was washed with 5 % NaOH (3 × 10 mL), H_2O (10 mL) and brine (10 mL). Drying over $MgSO_4$ and concentration *in vacuo* produced crude **1** as a light orange liquid. Distillation of the crude material by short path distillation gave pure **1** as a clear, colorless liquid: 3.82 g (78 %); bp 74-82 °C (0.15 mm).

(+/–)-endo-2-(Diethoxyphosphoryl)bicyclo[2.2.1]heptane **6**

A mixture of diethyl vinylphosphonate **1** (1.0 g, 4.5 mmol) and 25 mg of PtO_2 in 10 mL of ethyl acetate was hydrogenated under of H_2 (30 psi) in a Parr shaker for 18 h at room temperature. The reaction mixture was filtered and the solid PtO_2 was washed with ethyl acetate (20 mL). The filtrate was concentrated *in vacuo*, and the crude product was molecularly distilled (90 °C, 0.1 mm) to give purified *endo*-diethyl phosphonate **6**: 1.02 g (97 %); ^1H NMR (300 MHz, $CDCl_3$) δ 3.98-3.77 (m, 4 H, OCH_2), 2.33-2.24 (br s, 1 H), 2.15-2.07 (br s, 1 H), 1.98-1.67 (m, 3 H), 1.64-1.48 (m, 1 H), 1.40-0.99 (m, 11 H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 61.05 (d, J = 6.7, OCH_2) and 60.67 (d, J = 6.7, OCH_2), 40.44 (d, J = 18.9, C-7), 38.62 (d, J = 1.8, C-1), 37.13 (d, J = 148.3, C-2), 36.85 (d, J = 7.3,

C-4), 30.61 (C-3), 28.94 (C-5), 25.03 (d, J = 5.5, C-6), 16.27 (d, J = 6.1, CH_3) and 16.24 (d, J = 5.5, CH_3). ^{31}P NMR (121 MHz, $CDCl_3$) δ 35.0 GC-MS: m/e (%); 232 (M+, 17), 204 (10), 166 (61), 165 (100), 152 (53), 139 (29), 138 (52), 137 (33), 111 (39), 109 (85), 95 (28), 67 (39), 65 (41). HRFAB in Gly/TFA Calcd for $C_{11}H_{22}O_3P$ [M+1]: 233.1307. Found: 233.1314.

(+/–)-endo-2-(Dichlorophosphoryl)bicyclo[2.2.1]heptane 7

Phosphorus pentachloride was added to **6** (1.80 g, 7.76 mmol) in small portions over a 15 min period. The resultant heterogeneous mixture was heated to 105 °C for 2 h. The reaction was complete as determined by ^{31}P NMR spectroscopy. Phosphorus oxychloride and a small amount of excess PCl_5 were distilled (bp 25-60 °C, 20 mm). The product (1.40 g, 85 %) was distilled (66-68 °C, 0.1 mm). ^1H NMR (300 MHz, $CDCl_3$) δ 2.15-1.96 (m, 2 H), 1.78-1.61 (m, 2 H), 1.38-0.46 (m, 7 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 54.87 (d, J = 98.3, C-2), 40.65 (d, J = 23.8, C-7), 40.47 (d, J = 2.4, C-1), 37.35 (d, J = 7.9, C-4), 31.47 (C-3), 28.62 (C-5), 24.84 (C-6); ^{31}P NMR (121 MHz, $CDCl_3$ in agreement with lit [12a]) δ 56.5. Anal. Calcd for $C_7H_{11}Cl_2O_3P$: C, 39.46; H, 5.20. Found: C, 39.11; H, 5.02.

(+/–)-endo- and exo-2-(Dichlorophosphoryl)bicyclo[2.2.1]heptane 7 and 8 *(mixture)*

Phosphorus pentachloride (11.9 g, 57 mmol) was added to diethyl phosphonate **6** (6.0 g, 26 mmol) at room temperature over a 15 min period. The resultant mixture was heated to 120-140 °C for 4 h. After the reaction mixture cooled to room temperature, phosphorus oxychloride and the excess PCl_5 were distilled (bp 40-46 °C, 20 mm). Distillation of the crude product gave dichlorophosphonate **7** as a 3:1 mixture of endo to exo isomers: yield 3.22 g (58%); bp 66 °C (0.1 mm). ^{31}P NMR (121 MHz, $CDCl_3$ in agreement with lit [12a]) δ 56.5 (endo-isomer **7**) and δ 56.0 (exo-isomer **8**) in a 3:1 ratio.

Isomerization of 7 and **8**. Pure **7** was treated with 1 eq. PCl_5 at 120-140 °C. After 4 h a 30 % conversion to the exo isomer was observed as determined by ^{31}P NMR integration. Pure **8** was treated with 1 eq. PCl_5 at 120-140 °C. After 4 h a 10 % conversion to the endo isomer was observed as determined by ^{31}P NMR integration. When 30 mg pure **7**, or 30 mg **7** containing 0.2 eq. phosphorus of oxychloride was heated at 140 °C for 4 h in a dry NMR tube no isomerization was observed as determined by ^{31}P NMR spectroscopy.

Acknowledgements

SEC would like to thank S.C Johnson Wax for support for this project. The Department of Education National Needs Fellowship Program P200A-90035-91 is thanked for a Summer Research Fellowship for S.M.L. Mass spectrometry was provided by the Washington University Mass Spetrometry Resource, a NIH Research Resource (Grant No. p41RR0954). We wish to thank Chris Morrissey for his synthetic help.

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