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Synthesis and structural characterization of a thioether-bridged *commo*-metallabis(dicarbollide) species: a model system for Venus flytrap cluster reagents [1]

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Abstract

Recently we reported the synthesis and characterization of the first in a series of ether-bridged *commo*-metallabisdicarbollide complexes for use as model compounds in the development of radiotransition metal carriers. We now report the synthesis and crystal structure of a thioether analog, *meso*-**4**. The methyltriphenylphosphonium salt of *meso*-**4** was prepared in a four-step process from dipropargyl thioether. Compound *meso*-**4** crystallized in the monoclinic space group $P2_1/c$ with $a = 13.710(7)$, $b = 18.233(10)$ and $c = 13.896(7)$ Å, $\beta = 99.43(2)°$, $V = 3427$ Å^3, and $Z = 4$. Data were collected using MoK$_\alpha$ radiation to a maximum $2\theta = 60°$, giving 8135 unique reflections. The structure was solved using direct methods. The final discrepancy index was $R = 0.069$, $R_w = 0.088$ for 4902 independent reflections with $I > 3\sigma(I)$. The thioether, **4**, was subsequently oxidized to yield the corresponding sulphone, **5**. © 1998 Elsevier Science S.A.

Keywords: Ether-bridged *commo*-metallabisdicarbollide complex; Radiotransition; Dipropargyl thioether

1. Introduction

Functionalized Venus flytrap complexes (VFC) have been found to be useful in binding radiotransition metals to tumor-associated monoclonal antibodies, thereby providing conjugates which may prove to be clinically useful in the radio-immunodetection and radio-immunotherapy of cancer [1,2]. Until recently, the preparation of these compounds has proven to be daunting due to the required use of numerous protection and deprotection steps [3,4]. This problem was mitigated with the introduction of an ether linkage connecting the two carboranyl cages [5]. This improved synthesis resulted in a more direct route to VFC reagents which requires fewer steps and results in higher yields of the desired compounds. In a similar vein, it was thought that the thioether-bridged species presented here might provide an equally beneficial model for the synthesis of VFC reagents.

2. Experimental

2.1. General considerations

Dipropargyl thioether was prepared according to literature methods [6–8]. All reactions were performed under an atmosphere of nitrogen. Standard glovebox, Schlenk and vacuum line techniques were used for all manipulations of air and moisture-sensitive compounds. Reaction solvents were reagent grade and distilled from appropriate drying agents under nitrogen prior to use. Tetrahydrofuran (THF) and toluene were distilled from sodium benzophenone ketyl; diethyl sulfide was distilled from lithium aluminum hydride. Deuterated solvents were obtained from Cambridge Isotope Laboratories, Knoxville, TN. Sodium hydride (Aldrich) was used as received. Cobalt chloride (Cerac) was obtained in

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argon-filled vessels and was used without further purification. ^{1}H NMR spectra were recorded on either a Bruker AC-200 or ARX-400 spectrometer, as indicated. ^{13}C NMR spectra were recorded on a Bruker ARX-400 spectrometer. ^{11}B NMR were recorded on a Bruker-500 spectrometer. Infrared spectra were recorded on a Nicolet 205 FT-IR instrument. Negative FAB mass spectra were obtained from the Mass Spectrometry Facility at the University of California, Los Angeles.

2.2. Preparation of [1-(closo-1,2-C$_2$B$_{10}$H$_{11}$)-CH$_2$]$_2$S (1)

To a 1-l flask containing a solution of decaborane (12.2 g, 100 mmol) in toluene (500 ml), was added diethyl sulfide (21.5 ml, 200 mmol). Stirring was initiated, and the mixture was refluxed for two days. After the mixture had cooled, dipropargyl sulfide (5.42 g, 47.5 mmol) was added. The mixture was heated to reflux over a four-day period, cooled to room temperature and diethyl sulfide removed in vacuo. The residue was dissolved in toluene and washed with a 10% solution of potassium hydroxide ($\sim$ 300 ml). IR (Nujol, cm^{-1}): 3204(w), 3057(m), 2981(s), 2728(w), 2586(s), 1461(s), 1406(m), 1380(s). ^{1}H NMR (200 MHz; CDCl$_3$): $\delta = 3.83$ (s, 2H, Cb CH), $\delta = 3.36$(s, 4H, α-CH$_2$). ^{13}C{^{1}H} NMR (100 MHz; CDCl$_3$): $\delta = 72.9$, $\delta = 59.8$, $\delta = 40.2$. ^{11}B{^{1}H} NMR (160 MHz, acetone) $\delta = -1.32$ (d, 1B), $\delta = -4.03$ (d, 1B), $\delta = -7.08$ (d, 2B), $\delta = -9.77$ (d, 2B), $\delta = -10.6$ (d, 2B), $\delta = -11.4$ (d, 2B). High resolution electron ionization mass spectroscopy (EIMS) calculated mass for C$_6$H$_{26}^{10}$B$_3^{11}$B$_{17}$S m/e 347.37; observed m/e 347.37.

2.3. Preparation of mixed stereoisomers of 2

To a solution of KOH pellets (3.29 g, 58.6 mmol) in ethanol (100 ml) was added 1 (2.0 g, 5.8 mmol). The solution was heated at reflux overnight and cooled. Dry ice was added to the solution until no more precipitate was formed. The potassium bicarbonate was separated by filtration and washed with ethanol (3 × 50 ml). The filtrates were combined and added to a solution of trimethylamine hydrochloride (1.75 g, 18.3 mmol). The solids were separated by filtration, dried, and recrystallized from hot water to give 2 in 30.6% yield (0.936 g, 1.77 mmol) without separation of isomers. IR (Nujol, cm^{-1}): 3617(w), 3153(s), 2988(m), 2902(w), 2842(w), 2524(s), 1611(w), 1472(s), 1399(m), 1359(w), 1267(s), 737(s). ^{1}H NMR (400 MHz, d-acetone): $\delta = 3.11$ (s, 18H, NC–H), $\delta = 2.9$ (dd, 2H, α-CH$_2$ (R)(S) or meso) $\delta = 2.63$ (dd, 2H, α-CH$_2$ (R)(S) or meso) $\delta = 1.92$ (s, 2H, Cb C–H). ^{13}C{^{1}H} NMR (100 MHz, CD$_3$CN, all isomers): $\delta = 58.7$, $\delta = 58.4$, $\delta = 46.4$, $\delta = 45.8$, $\delta = 44.8$, $\delta = 42.6$, $\delta = 42.4$. ^{11}B{^{1}H} NMR (160 MHz, acetone): $\delta = -8.97$ (d, 4B), $\delta = -12.0$ (d, 2B), $\delta = $

-15.7 (d, 2B), $\delta = -16.9$ (d, 4B), $\delta = -21.2$ (d, 2B), $\delta = -31.9$ (d, 2B), $\delta = -35.6$ (d, 2B). High resolution negative ion mass spectroscopy (FABMS) calculated mass for C$_6$H$_{26}^{10}$B$_3^{11}$B$_{15}$S m/e 325.35; observed m/e 325.35.

2.4. Preparation of mixed stereoisomers of 3 and 4

To a solution of mixed stereoisomers of 2 (0.504 g, 0.946 mmol) in THF (100 ml) was added NaH (0.0908 g, 3.78 mmol). The reaction mixture was stirred at reflux overnight and then cooled. The solution was filtered through a glass frit yielding a solution of the stereoisomers of 3. To the solution was added anhydrous cobaltous chloride (0.187 g, 1.44 mmol). The solution gradually changed from pale blue to brown over a 12 h period. The solution was refluxed overnight, cooled, and filtered to remove cobalt metal and KCl. After removal of the solvent in vacuo, the residue was dissolved in hot water. The resulting aqueous solution was filtered, and the orange solution was added to an aqueous solution of methyltriphenylphosphonium bromide (0.77 g, 2.2 mmol). The aqueous solution was extracted with methylene chloride, dried over magnesium sulfate and chromatographed (silica gel) using methylene chloride, without separation of isomers. The product was recrystallized from a heptane/dichloromethane solution to give orange platelets of 4 (mixture of stereoisomers) in 44% yield (0.16 g, 0.42 mmol), IR (Nujol, cm^{-1}): 2931(s), 2728(s), 2557(s), 1460(s), 1378(m), 1111(w), 1004(w). ^{1}H NMR (400 MHz, CDCl$_3$): $\delta = 7.70$ (m, 15H, Ph), $\delta = 3.47$ (dd, 4H, α-CH$_2$ (R)(S) or meso), $\delta = 3.37$ (dd, 4H, α-CH$_2$ (R)(S) or meso), $\delta = 2.88$ (d, 3H, $J_{PH} = 13.0$, PCH$_3$). ^{13}C{^{1}H} NMR (d-acetone) $\delta = 135.1$, $\delta = 133.3$, $\delta = 130.3$, $\delta = 119.8$, $\delta = 67.7$, $\delta = 55.4$, $\delta = 54.8$, $\delta = 41.6$, $\delta = 7.83$. ^{11}B{^{1}H} NMR (160 MHz, acetone) $\delta = 7.23$ (d, 1B), $\delta = 5.82$ (d, 1B), $\delta = 1.74$ (d, 2B), $\delta = -3.18$ (d, 1B), $\delta = -5.61$ (d, 4B), $\delta = -6.69$ (d, 3B), $\delta = -7.95$ (d, 1B), $\delta = -12.5$ (d, 2B), $\delta = -16.4$ (d, 1B), $\delta = -17.7$ (d, 2B). High resolution negative ion mass spectroscopy (FABMS) calculated mass for C$_6$H$_{24}^{10}$B$_3^{11}$B$_{15}$SCo m/e 382.27; observed m/e 382.27.

2.5. Preparation of mixed stereoisomers of (5)

To a solution of cobalt thioether (0.074 g, 0.11 mmol) in methylene chloride (30 ml) was added an excess of 80% m-chloroperbenzoic acid (0.084 g, 0.49 mmol). The mixture was stirred at reflux for two and a half days and then cooled. The aqueous mixture was extracted with a saturated solution of sodium thiosulfate, dried over magnesium sulfate and chromatographed (silica gel) using 30% diethyl ether in methylene chloride to yield the orange sulfone 5 (0.009 g,

0.02 mmol). IR (Nujol, cm^{-1}): 2568(s), 2362(w), 1457(w), 1441(m), 1316(m), 1121(s), 747(m), 687(w). ^{1}H NMR (200 MHz, CDCl$_3$) $\delta = 7.61$ (m, 15H, Ph), $\delta = 4.38$(dd, 4H, α-CH$_2$ (R)(S) or *meso*), $\delta = 4.21$ (dd, 4H, α-CH$_2$ (R)(S) or *meso*), $\delta = 3.77$ (s, 2H, Cb CH), $\delta = 2.82$ (d, 3H, $J_{PH} = 13.1$, PCH$_3$). ^{13}C{^{1}H} NMR (CDCl$_3$) $\delta = 135.6$, $\delta = 133.1$, $\delta = 130.7$, $\delta = 118.1$, $\delta = 77.2$, $\delta = 9.95$. ^{11}B{^{1}H} NMR (160 MHz, acetone) $\delta = 9.33$ (d, 2B), $\delta = 4.35$ (d, 2B), $\delta = -1.66$ (d, 2B), $\delta = -3.95$ (d, 6B), $\delta = -12.0$ (d, 2B), $\delta = -14.8$ (d, 2B) $\delta = -16.1$ (d, 2B). High resolution negative ion mass spectroscopy (FABMS) calculated mass for C$_6$H$_{24}^{10}$B$_3^{11}$B$_{15}$O$_2$SCo $m/e = 414.25$; observed $m/e = 414.26$.

2.6. Collection and reduction of X-ray data for meso-*4*

A colorless crystal obtained from a heptane/CH$_2$Cl$_2$ solution which proved to be *meso*-**4**, was affixed to a fiber and mounted on a Huber diffractometer constructed by Prof. C.E. Strouse of this department. Systematic absences were found for $0k0$ reflections for which $k \neq 2n$ and for $h01$ reflections for which $1 \neq 2n$. Unit cell parameters were determined from a least-squares fit of 54 accurately centered reflections (9.4 <

Table 1
Details of crystallographic data collection for *meso*-**4**

Empirical formula	C$_{25}$H$_{42}$B$_{18}$CoSP
Fw	658.58
Temp.	25
Crystal size (mm)	$0.25 \times 0.30 \times 0.42$
Normal to faces	100, 001, 010
Crystal system	parallelepiped
Space group	$P2_1/c$
a (Å)	13.710 (7)
b (Å)	18.233 (10)
c (Å)	13.896 (7)
β (deg)	99.43 (2)
V (Å^3)	3427
Z	4
d_{calc} (g/cm^3)	1.03
Radiation (graphite monochromator)	Mo Kα (0.7107 Å)
μ (cm^{-1})	6.09
Scan rate (deg./min)	9
Scan width: below Kα_1 (deg.)	1.3
Above Kα_2 (deg.)	1.6
2θ max (deg.)	60
Data collected	$+h, +k, \pm l$
No. of unique reflections	8135
No. of observed reflections, $I > 3\sigma(I)$	4902
No. of parameters refined	383
R^a	0.069
R_w^b	0.088
GOF^c	2.48

$^a R = \Sigma||F_o| - |F_c||/|F_o|$.
$^b R_w = [\Sigma w(|F_o| - |F_c|)^2/\Sigma w(|F_o|^2)]^{1/2}$.
^{c} GOF $= [\Sigma w(|F_o| - |F_c|)^2/(N_o - N_v)]^{1/2}$, where $w = 1/\sigma^2|F_o|$.

Table 2
Selected bond lengths and angles for *meso*-**4**

Lengths (Å)

Co(1)–C(1)	2.067(5)	Co(1)–C(2)	2.079(5)
Co(1)–B(4)	2.115(6)	Co(1)–B(7)	2.087(7)
Co(1)–B(8)	2.103(6)	C(1)–C(2)	1.604(7)
C(1)–B(4)	1.727(8)	C(1)–B(5)	1.7(9)
B(5)–B(6)	1.759(10)	C(1)–C(1B)	1.524(8)
C(1B)–S(2B)	1.743(7)	S(2B)–C(3B)	1.781(8)

Angles (deg.)

C(1)–Co(1)–C(1')	104(2)	Co(1)–C(1)–C(1B)	114.5(4)
C(1)–C(1B)–S(2B)	120.2(4)	C(1B)–S(2B)–C(3B)	112.8(3)

$2\theta < 20.4°$). These dimensions and other parameters, including conditions of data collection, are summarized in Table 1. Data were collected at 25°C in the θ–2θ scan mode. Three intense reflections (0 8 1, 5 3 -1, 1 3 6) were monitored every 97 reflections to check stability. Intensities of these reflections did not decay during the course of the experiment (74.6 h). Of the 8135 unique reflections measured, 4902 were considered observed ($I > 3\sigma(I)$) and were used in the subsequent structure analysis. Data were corrected for Lorentz and polarization effects and for secondary extinction and absorption. Programs used in this work include locally modified versions of the following programs: CARESS (Broach, Coppens, Becker and Blessing), peak profile analysis, Lorentz and polarization corrections; ORFLS (Busing, Martin and Levy), structure factor calculation and full-matrix least-squares refinement; SHELX76 (Sheldrick), a crystal structure package; SHELX86 (Sheldrick), a crystal structure solution package; ABSORB, a local absorption correction based on crystal shape, orientation and content; and ORTEP (Johnson).

2.7. Solution and refinement of the structure of meso-*4*

Atoms were located by use of direct methods (SHELX86). All calculations were performed on a VAX 3100 computer in the J.D. McCullough X-ray Crystallography Laboratory. All nonhydrogen atoms were refined with anisotropic parameters. The phenyl rings of the cation have been treated as rigid C$_6$H$_5$ groups, angles = 120°, C–C = 1.395 Å, C–H = 1.0 Å (Table 2). H atoms of methylene groups were placed in calculated positions. All other H atoms were located and were included, but parameters were not refined. H atoms were assigned isotropic displacement values based approximately on the value for the attached atom. Scattering factors for H were obtained from Stewart et al. [9] and for other atoms were taken from the International Tables for X-ray Crystallography [10]. Anomalous dispersion terms were applied for Co and S. The largest peak on a final difference electron density map

Table 3
Position and displacement parameters for compound meso-**4**

Atom	x	y	z	$U11$ or $< u$ Sq $>$	$U22$	$U33$	$U12$	$U13$	$U23$	U_{eq}
CO(1)	0.16640(4)	0.24530(4)	0.09782(4)	0.0387(3)	0.0443(4)	0.0366(3)	− 0.0029(3)	0.0057(2)	− 0.0016(3)	0.0399(1)
C(1B)	− 0.0015(4)	0.2946(4)	− 0.0607(4)	0.066(4)	0.093(5)	0.054(3)	− 0.017(3)	− 0.010(3)	0.016(3)	0.073(2)
S(2B)	− 0.07889(15)	0.22133(13)	− 0.04453(18)	0.0888(14)	0.1284(19)	0.1422(19)	− 0.0413(13)	− 0.0609(13)	0.0511(15)	0.1288(7)
C(3b)	− 0.0252(5)	0.1600(4)	0.0490(6)	0.060(4)	0.104(6)	0.144(7)	− 0.020(4)	0.007(4)	0.023(5)	0.104(3)
C(1)	0.0862(4)	0.1491(3)	0.0759(4)	0.046(3)	0.057(3)	0.065(4)	− 0.011(3)	0.000(3)	0.000(3)	0.057(1)
C(2)	0.1579(4)	0.1605(3)	− 0.0032(4)	0.078(4)	0.047(3)	0.053(3)	− 0.019(3)	0.017(3)	− 0.011(3)	0.058(1)
B(4)	0.1487(5)	0.1610(4)	0.1933(4)	0.076(4)	0.060(4)	0.044(3)	0.002(3)	0.021(3)	0.005(3)	0.059(2)
B(5)	0.1149(5)	0.0715(4)	0.1424(5)	0.071(5)	0.065(4)	0.069(4)	− 0.017(4)	0.016(4)	0.008(4)	0.068(2)
B(6)	0.1217(6)	0.0731(4)	0.0171(5)	0.096(5)	0.053(4)	0.062(4)	− 0.025(4)	0.004(4)	− 0.006(3)	0.071(2)
B(7)	0.2736(5)	0.1798(3)	0.0498(5)	0.068(4)	0.044(3)	0.083(5)	− 0.005(3)	0.034(4)	− 0.017(3)	0.063(2)
B(8)	0.2738(4)	0.1776(4)	0.1792(5)	0.053(4)	0.042(3)	0.070(4)	0.001(3)	− 0.010(3)	− 0.004(3)	0.057(2)
B(9)	0.2353(6)	0.0883(3)	0.2060(5)	0.087(5)	0.047(4)	0.060(4)	0.005(3)	− 0.004(4)	0.001(3)	0.066(2)
B(10)	0.2172(5)	0.0329(4)	0.0997(5)	0.083(5)	0.046(4)	0.071(4)	− 0.014(3)	0.013(4)	− 0.006(3)	0.067(2)
B(11)	0.2403(6)	0.0910(4)	0.0038(5)	0.108(6)	0.049(4)	0.074(5)	− 0.013(4)	0.038(4)	− 0.016(4)	0.074(2)
B(12)	0.3119(5)	0.0999(4)	0.1164(6)	0.062(4)	0.041(4)	0.105(6)	0.001(3)	0.014(4)	− 0.004(4)	0.069(2)
C(1′)	0.0724(3)	0.3239(3)	0.0260(3)	0.041(3)	0.065(3)	0.046(3)	− 0.002(3)	0.000(2)	0.006(3)	0.052(1)
C(2′)	0.1880(4)	0.3332(3)	0.0126(4)	0.052(3)	0.050(3)	0.053(3)	− 0.002(2)	0.011(2)	0.003(3)	0.051(1)
B(4′)	0.0637(4)	0.3171(4)	0.1469(4)	0.047(3)	0.066(4)	0.053(4)	0.013(3)	0.014(3)	0.004(3)	0.055(2)
B(5′)	0.0333(5)	0.4000(4)	0.0825(5)	0.054(4)	0.068(4)	0.068(4)	0.020(3)	0.009(3)	0.005(3)	0.063(2)
B(6′)	0.1118(5)	0.4107(4)	− 0.0053(5)	0.060(4)	0.060(4)	0.061(4)	0.006(3)	0.007(3)	0.009(3)	0.061(2)
B(7′)	0.2671(4)	0.3321(3)	0.1234(4)	0.045(3)	0.048(3)	0.051(3)	0.001(3)	0.004(3)	− 0.007(3)	0.049(1)
B(8′)	0.1872(5)	0.3229(3)	0.2126(4)	0.065(4)	0.050(4)	0.048(3)	0.005(3)	0.003(3)	− 0.008(3)	0.055(2)
B(9′)	0.1058(5)	0.4008(4)	0.1991(5)	0.075(5)	0.064(4)	0.058(4)	0.024(4)	0.016(4)	− 0.005(3)	0.065(2)
B(10′)	0.1379(5)	0.4598(4)	0.1058(5)	0.073(5)	0.055(4)	0.072(5)	0.013(3)	0.010(4)	− 0.001(3)	0.067(2)
B(11′)	0.2350(5)	0.4155(3)	0.0571(5)	0.062(4)	0.047(4)	0.073(4)	− 0.001(3)	0.017(3)	− 0.005(3)	0.060(2)
B(12′)	0.2323(5)	0.4109(3)	0.1846(5)	0.061(4)	0.047(4)	0.068(4)	0.004(3)	0.004(3)	− 0.009(3)	0.059(2)
P(1)	0.68421(10)	0.33274(7)	0.16272(10)	0.0453(7)	0.0408(7)	0.0594(8)	− 0.0009(6)	0.0059(6)	− 0.0008(6)	0.0488(3)
C(12)	0.5540(3)	0.2849(1)	0.2822(3)	0.070(4)	0.054(3)	0.061(4)	− 0.018(3)	0.009(3)	0.004(3)	0.062(2)
C(13)	0.4868(3)	0.2960(1)	0.3461(3)	0.065(4)	0.085(5)	0.064(4)	− 0.027(3)	0.011(3)	0.008(3)	0.071(2)
C(14)	0.4668(3)	0.3670(1)	0.3751(3)	0.054(3)	0.081(4)	0.065(4)	− 0.003(3)	0.013(3)	0.010(3)	0.066(2)
C(15)	0.5139(3)	0.4268(1)	0.3402(3)	0.069(4)	0.074(4)	0.079(4)	0.007(3)	0.021(3)	0.003(3)	0.073(2)
C(16)	0.5811(3)	0.4157(1)	0.2763(3)	0.064(4)	0.051(3)	0.071(4)	0.002(3)	0.021(3)	0.008(3)	0.061(2)
C(11)	0.6012(3)	0.3448(1)	0.2473(3)	0.042(3)	0.048(3)	0.047(3)	− 0.003(2)	0.001(2)	0.006(2)	0.047(1)
C(22)	0.5243(2)	0.3744(2)	0.0255(3)	0.063(4)	0.102(5)	0.065(4)	0.020(4)	0.016(3)	0.018(4)	0.076(2)
C(23)	0.4799(2)	0.3979(2)	− 0.0669(3)	0.085(5)	0.133(7)	0.070(4)	0.049(5)	0.005(4)	0.015(4)	0.097(2)
C(24)	0.5377(2)	0.4124(2)	− 0.1385(3)	0.131(6)	0.070(4)	0.061(4)	0.032(4)	0.016(4)	0.010(3)	0.087(2)
C(25)	0.6400(2)	0.4034(2)	− 0.1177(3)	0.115(6)	0.081(5)	0.074(5)	− 0.014(4)	0.034(4)	0.009(4)	0.088(2)
C(26)	0.6845(2)	0.3799(2)	− 0.0253(3)	0.073(4)	0.078(4)	0.075(4)	− 0.004(3)	0.024(3)	0.008(3)	0.074(2)
C(21)	0.6266(2)	0.3654(2)	0.0463(3)	0.050(3)	0.041(3)	0.057(3)	0.004(2)	0.014(2)	0.005(2)	0.049(1)
C(32)	0.6580(3)	0.1930(2)	0.0858(3)	0.106(5)	0.060(4)	0.103(6)	0.004(4)	− 0.034(4)	− 0.012(4)	0.095(2)
C(33)	0.6805(3)	0.1186(2)	0.0817(3)	0.154(7)	0.050(4)	0.101(6)	0.001(4)	− 0.032(5)	− 0.023(4)	0.108(3)
C(34)	0.7598(3)	0.0894(2)	0.1460(3)	0.112(5)	0.047(3)	0.075(4)	0.006(4)	0.025(4)	− 0.005(3)	0.077(2)
C(35)	0.8165(3)	0.1345(2)	0.2144(3)	0.099(5)	0.054(4)	0.077(4)	0.016(3)	0.001(4)	0.004(3)	0.078(2)
C(36)	0.7940(3)	0.2090(2)	0.2185(2)	0.077(4)	0.052(3)	0.068(4)	0.012(3)	− 0.007(3)	− 0.001(3)	0.068(2)
C(31)	0.7147(3)	0.2382(2)	0.1542(3)	0.059(3)	0.040(3)	0.055(3)	0.002(2)	0.005(2)	− 0.006(2)	0.052(1)
C(41)	0.7955(4)	0.3841(3)	0.2018(4)	0.046(3)	0.053(3)	0.083(4)	− 0.008(3)	0.010(3)	− 0.010(3)	0.061(1)
H(1B1)	− 0.045	0.337	− 0.086	0.07	*					
H(1B2)	0.038	0.279	− 0.112	0.07	*					
H(3B1)	− 0.053	0.111	0.030	0.08	*					
H(3B2)	− 0.048	0.177	0.110	0.08	*					
H(12)	0.568	0.234	0.261	0.07	*					
H(13)	0.453	0.253	0.371	0.07	*					
H(14)	0.419	0.375	0.421	0.07	*					
H(15)	0.500	0.478	0.361	0.08	*					
H(16)	0.615	0.459	0.251	0.08	*					
H(22)	0.483	0.364	0.077	0.08	*					
H(23)	0.407	0.404	− 0.082	0.09	*					
H(24)	0.506	0.429	− 0.205	0.09	*					
H(25)	0.682	0.414	− 0.169	0.09	*					
H(26)	0.758	0.373	− 0.010	0.09	*					
H(32)	0.601	0.214	0.040	0.09	*					
H(33)	0.640	0.086	0.033	0.10	*					
H(34)	0.776	0.036	0.143	0.10	*					
H(35)	0.873	0.114	0.261	0.09	*					
H(36)	0.835	0.241	0.268	0.07	*					
H(41A)	0.771	0.436	0.193	0.07	*					
H(41B)	0.849	0.376	0.162	0.07	*					
H(41C)	0.822	0.375	0.272	0.07	*					
H(4)	0.096	0.174	0.249	0.08	*					

Table 3 (continued)

Atom	x	y	z	$U11$ or $<u$ Sq $>$	$U22$	$U33$	$U12$	$U13$	$U23$	U_{eq}
H(5)	0.055	0.044	0.175	0.08	*					
H(6)	0.068	0.046	−0.045	0.08	*					
H(7)	0.313	0.216	0.000	0.08	*					
H(8)	0.328	0.207	0.239	0.08	*					
H(9)	0.257	0.055	0.285	0.08	*					
H(10)	0.223	−0.035	0.095	0.08	*					
H(12)	0.389	0.080	0.137	0.08	*					
H(11)	0.264	0.083	−0.072	0.08	*					
H(2′)	0.216	0.313	−0.043	0.08	*					
H(4′)	0.003	0.287	0.179	0.08	*					
H(5′)	−0.043	0.416	0.060	0.08	*					
H(6′)	0.093	0.420	−0.084	0.08	*					
H(7′)	0.344	0.318	0.130	0.08	*					
H(8′)	0.212	0.293	0.285	0.08	*					
H(9′)	0.076	0.428	0.268	0.08	*					
H(10′)	0.128	0.524	0.102	0.08	*					
H(11′)	0.286	0.436	0.021	0.08	*					
H(12′)	0.287	0.442	0.244	0.08	*					

Units of $U(I,J)$, U_{eq}, and isotropic $<u$ squared $>$ are Angstroms squared. Units of each e.s.d., in parentheses, are those of the least significant digit of the corresponding parameter.

U_{eq} defined as: $(1/3)[U11(aaa^*a^*) + U22(bbb^*b^*) + U33(ccc^*c^*) + 2U12(aba^*b^*cosgamma) + 2U13(aca^*c^*cosbeta) + 2U23(bcb^*c^*cosalpha)]$.

'Anisotropic temperature factor' defined as: $exp\{-2(pi\ squared)[U11(a^*a^*hh) + U22(b^*b^*kk) + U33(c^*c^*ll) + 2U12(a^*b^*hk) + 2U13(a^*c^*hl) + 2U23(b^*c^*kl)]\}$.

* Denotes an atom refined isotropically.

was 0.32 e $\mathring{A}^{-3}$. Final positional and thermal parameters for nonhydrogen atoms are given in Table 3.

3. Results and discussion

Compound **1** was easily formed by reacting the bis(diethylsulfide) derivative of decaborane with dipropargyl thioether utilizing well established methods [11–14]. Base degradation of **1** with potassium hydroxide in ethanol yielded a mixture of (*R*), (*S*) and *meso*-isomers corresponding to the dianionic species **2** (Scheme 1). The ^{1}H NMR spectrum of this mixture exhibited two sets of peaks for the *α*-methylene protons of the thioether bridge. Attempts to separate the isomers of **2** by chromatographic methods were unsuccessful and, therefore, resonances due to a specific isomer could not be definitively assigned. The ^{11}B and ^{13}C NMR spectra of **2** were as expected and no spectral differences between the isomers were observed. Treatment of **2** in THF with excess NaH afforded the desired bridged dicarbollide anion **3** (mixture of isomers). Filtration followed by the addition of anhydrous cobaltous chloride resulted in cobaltacarborane **4**, which was isolated in 44.1% yield. As seen for compound **2**, evidence for multiple isomers was observed in the ^{1}H NMR spectrum of **4**. Additionally, resonances due to (*R*), (*S*) and *meso*-isomers were apparent in the ^{13}C and ^{11}B NMR spectra. Resonance shifts in the ^{11}B NMR spectrum were consistent with a *commo*-carborane. Attempts to separate the isomers by column chromatography were unsuccessful. However, the crystal which was separated from the reaction mixture for X-ray crystallographic analysis was found to contain only the *meso*-isomer.

Initial studies involving the use of polymethylene bridges to link the carborane cages of Venus flytrap
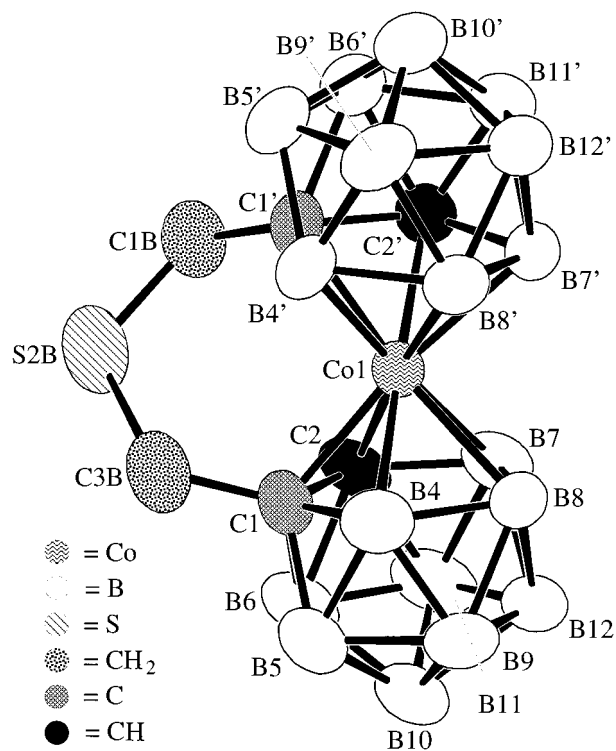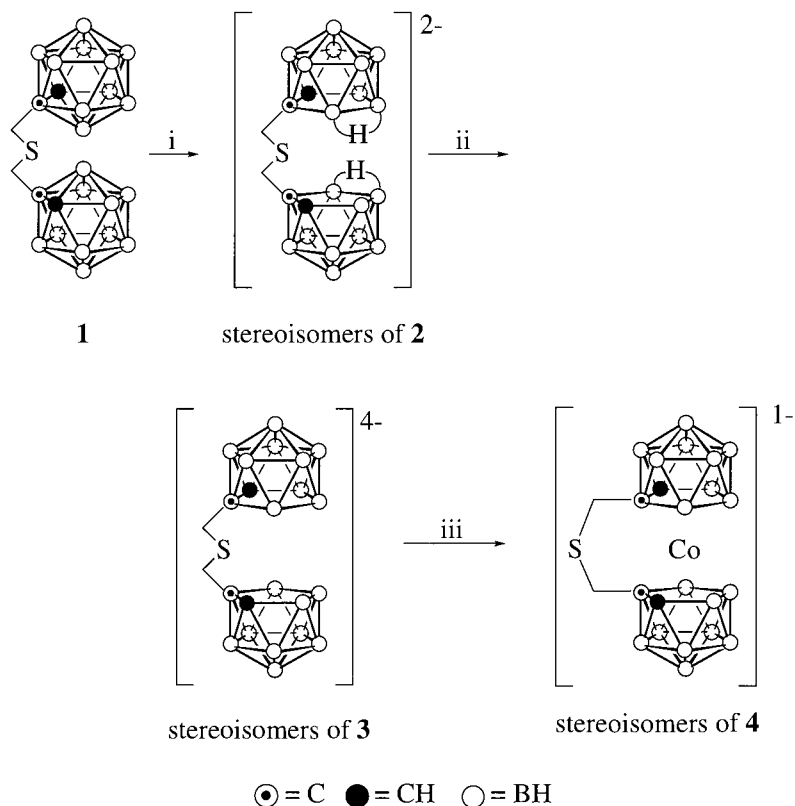

Fig. 1. ORTEP representation of the *meso*-**4** anion, showing the crystallographic numbering scheme. Hydrogen atoms are omitted for clarity.

i. (a) KOH, EtOH (b) HMe₃NCl; ii. NaH, THF; iii. (a) CoCl₂ (b) MePh₃PBr.
(A similar scheme for the *meso*-isomer also exists.)

Scheme 1.

reagents (VFC) indicated an optimal bridge length of four methylene units for metal complexation [3]; however, the bite-size of the 2-thiapropylene-bridged VFC, with only three atoms in the linking group, seems to have no such limitation. This is consistent with the 2-oxapropylene-bridged VFC which was reported in a previous communication [15].

In the molecular structure of *meso*-4 (Fig. 1), the cobalt atom is bound in an η^5-fashion to the five membered face of each of the two dicarbollide ligands. The distance from the cobalt atom to each mean plane of the dicarbollide cage faces is 1.48 Å, comparable to the other cobaltacarboranes [16]. Each of the bonding faces of the dicarbollide moieties is planar to within 0.026(7) or 0.010(6) Å (unprimed and primed atoms, respectively) and the angle between the normals to these planes is 8.1°.

The two icosahedra that share the cobalt atom as a
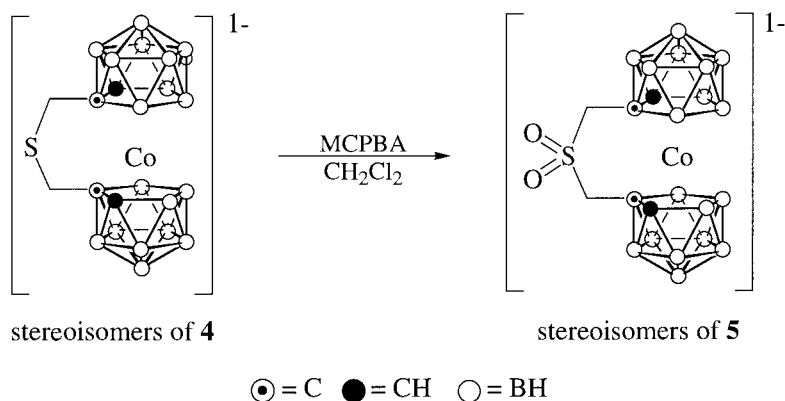
Scheme 2.

common apex in *meso*-**4** are further linked by a –CH$_2$SCH$_2$-bridge that spans from C(1) to C(1′). The sulfur atom does not attain the optimal conformation required for proper molecular overlap and is observed to be 3.638(2) Å from the cobalt atom, precluding any bonding interaction.

Oxidation of the cobaltadicarbollide thioether, (*R*), (*S*) and *meso*-**4**, with *m*-chloroperoxybenzoic acid in methylene chloride resulted in the production of the corresponding sulfone, (*R*), (*S*) and *meso*-**5** (Scheme 2). Strong absorption bands due to the symmetric and asymmetric stretches of the sulfone are clearly visible in the IR spectrum at 1121 and 1316 cm^{-1}, respectively. The ^{1}H NMR spectrum of compound (*R*), (*S*) and *meso*-**5** exhibited two sets of peaks for the α-methylene protons of the bridge due to the presence of isomers. Additionally, resonances due to (*R*), (*S*) and *meso*-isomers were apparent in the ^{13}C and ^{11}B NMR spectra. Resonance shifts in the ^{11}B NMR spectrum were consistent with a *commo*-carborane. Attempts to separate the isomers by column chromatography were unsuccessful.

4. Conclusions

The complex **4** described in this report represents the first in a series of thioether-bridged and carbon-linked metallacarboranes to be used as model compounds in the development of radiotransition metal carriers for the antibody-mediated γ-imaging and β-therapy of tumors [1,2]. We are currently in the process of characterizing other metal complexes of **2**. Results of these studies will be published elsewhere. We are also developing other thioether-linked VFCs that can be readily functionalized and conjugated to monoclonal antibodies.

References

[1] M.F. Hawthorne, A. Varadarajan, C.B. Knobler, S. Chakrabarti, J. Am. Chem. Soc. 112 (1990) 5365–5366.

[2] R.J. Paxton, B.G. Beatty, M.F. Hawthorne, A. Varadarajan, L.E. Williams, F.L. Curtis, C.B. Knobler, J.D. Beatty, J.E. Shively, Proc. Natl. Acad. Sci. 88 (1991) 3387–3391.

[3] F.A. Gomez, S.E. Johnson, C.B. Knobler, M.F. Hawthorne, Inorg. Chem. 31 (1992) 3558–3567.

[4] A. Varadarajan, S.E. Johnson, F.A. Gomez, S. Chakrabarti, C.B. Knobler, M.F. Hawthorne, J. Am. Chem. Soc. 114 (1992) 9003–9011.

[5] D.E. Harwell, J. Nabakka, C.B. Knobler, M.F. Hawthorne, Can. J. Chem. 73 (1995) 1044–1049.

[6] K. Sato, Nihon Kagaku Zasshi 76 (1955) 1404–1406.

[7] K. Mikami, H. Matsueda, T. Nakai, Synlett (1993) pp. 23–25.

[8] Y.S. Gal, S.K. Choi, J. Polym. Sci. 26 (1988) 115–121.

[9] R.F. Stewart, E.R. Davidson, W.T. Simpson, J. Chem. Phys. 42 (1965) 3175.

[10] International Tables for X-ray Crystallography, Vol. IV, Kynoch Press, Birmingham, England, 1974.

[11] M.M. Fein, J. Bobinski, N. Mayes, N. Schwartz, M.S. Cohen, Inorg. Chem. 2 (1963) 1111–1115.

[12] T.L. Heying, J.W. Ager Jr., S.L. Clark, D.J. Mangold, H.L. Goldstein, M. Hillman, R.J. Polak, J.W. Szymanski, Inorg. Chem. 2 (1963) 1089–1092.

[13] L.I. Zakharkin, V.I. Stanko, V.A. Brattsev, Y.A. Chapovskii, O.Y. Okhlobystin, Izv. Akad. Nauk SSSR, Ser. Khim. (1963) 2238 pp.

[14] L.I. Zakharkin, V.I. Stanko, V.A. Brattsev, Y.A. Chapovskii, Y.T. Struchkov, Izv. Akad. Nauk SSSR, Ser. Khim. (1963) 2069 pp.

[15] D.E. Harwell, J. Nabakka, C.B. Knobler, M.F. Hawthorne, Can. J. Chem.-Revue Canadienne De Chimie 73 (1995) 1044–1049.

[16] A. Zalkin, T.E. Hopkins, D.H. Templeton, Inorg. Chem. 6 (1967) 1911.