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New Economical, Convenient Procedures for the Synthesis of Catecholborane[†]

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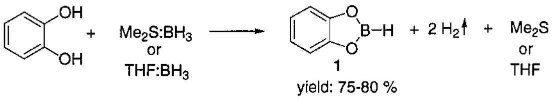
Abstract:

Catecholborane was conveniently synthesized by the reaction of tri-*O*-phenylene bis-borate (2) with diborane in triglyme or tetraglyme at moderate temperatures (70−80 °C). The product, catecholborane, can be distilled out in 85% yield with >97% purity. The tri-*O*-phenylene bis-borate also reacts with borane−Lewis base complexes, such as BH_3:DMS, BH_3:THF, and BH_3:NR_3, with or without solvent, providing catecholborane of high purity in good yields.

Introduction

Catecholborane is one of the most versatile boron hydride reagents available for synthetic chemists. It has found a multitude of applications as a selective reducing and hydroborating agent.[2] It has been effectively used in the preparation of alkyl- and alkenylboronic acids.[3] Particularly its usage in conjunction with chiral oxazaborolidine and chiral transition-metal complex catalysts provides a unique tool for the synthesis of chiral alcohols in very high enantioselectivities.[4]

Although catecholborane can be prepared by other procedures,[5] the preferred synthesis has been by the reaction of catechol with borane−tetrahydrofuran or borane−methyl sulfide (eq 1).[2a,6]



(1)

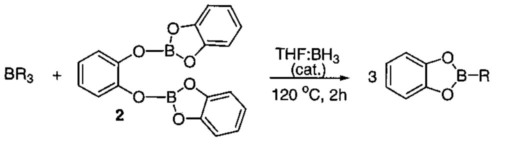
The product catecholborane was isolated by distillation (bp 50 °C/50 mmHg). The catecholborane thus obtained is moisture-sensitive but is stable to dry air and can be stored at 0 °C for long periods. However, this procedure does suffer from some disadvantages, such as the waste of two equivalents of active hydride and the liberation of large amounts of hydrogen, which may be of concern in large-scale applications. Also, the commercially available catecholborane contains considerable amounts of borate impurities (15−20%). As a result, in its synthetic applications, either it should be used in excess or freshly distilled before use, when borate (**2**) impurity interferes with the main reaction. Accordingly, it was decided to explore more economic and convenient options devoid of these problems for the synthesis of this valuable borane reagent.

Results and Discussion

Recently, it was reported that catecholborane exchanges with trialkylboranes at room temperature in dichloromethane (eq 2).[7]

(2)

This exchange presumably occurs via the transfer of the catechol moiety from >B−H to >B−R. In our earlier studies from this laboratory, we reported that trialkylboranes exchange the alkyl group with tri-*O*-phenylene bis-borate (**2**) in the presence of catalytic amounts of THF:BH_3 (eq 3).[2a]



(3)

These observations prompted us to examine whether this type of exchange process is possible with BH_3 and borate (**2**), possibly offering an effective route for the synthesis of catecholborane itself without any waste of active hydride. Accordingly, borate (**2**) was conveniently prepared from catechol and boric acid following the literature reports as outlined in eq 4.[8] The reaction of catechol (3 equiv) and boric acid (1 equiv) in toluene under reflux conditions with removal of water provided the borate **2**. The ^{11}B NMR examination showed a clean single peak at +22.2 ppm (singlet). The synthesis of catecholborane was envisioned through the exchange of>B−H of BH_3 to >B−O− of borate **2** (eq 4).

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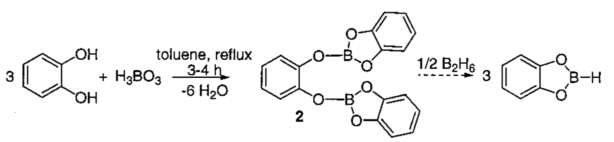


(4)

Initially, the synthesis of catecholborane was attempted by the reaction of borate **2** (white solid, mp 102 °C) with diborane[9] at room temperature. However, the reaction proceeds very slowly at room temperature, but the exchange was greatly accelerated at higher temperatures. The reaction proceeds very rapidly at 102 °C, at which temperature the borate **2** melts, and catecholborane was obtained in 80% yield after distillation. However, diborane gas is sensitive to high temperatures in the absence of Lewis bases and may result in the formation of unwanted higher boranes. This problem was addressed by using an inert solvent that dissolves borate **2** and does not interfere with the isolation procedure.

The reaction temperatures could be brought down considerably by performing the reaction in glymes, such as di-, tri-, or tetraglymes, in which the borate **2** is somewhat soluble. Thus, the borate **2** was taken in tetraglyme, and diborane gas was passed into this mixture. The diborane gas readily reacts with the tetraglyme solution of borate **2** at 70 °C, and catecholborane was formed in 85% yield, and 15% of unreacted borate **2** was also observed (by ^{11}B NMR, +22.3 ppm). The catecholborane thus obtained could be distilled out from tetraglyme conveniently in 83% yield with 98% chemical purity (by ^{11}B NMR, +28.2 ppm, d).[10] The ^{11}B NMR examination of the residual tetraglyme showed only the presence of unreacted borate **2** (15%). To this tetraglyme solution, additional borate **2** (85%) can be added and treated with diborane (Scheme 1). This provides an ideal procedure for the synthesis of catecholborane. The other glymes, such as diglyme and triglyme, also give comparable results, and the preparation of catecholborane was carried out without any problem, with its isolation. However, monoglyme, a low-boiling glyme with a boiling point close to that of catecholborane, complicates the isolation of catecholborane. This reaction can be also performed in toluene, but here also the isolation of catecholborane is difficult, and therefore these procedures are preferred for in situ preparation and utilization.

Further, the exchange of >B−H of borane to >B−O− of tri-O-phenylene bis-borate can be also effected by using borane−Lewis bases as the >B−H source, in solvents that are inert to borane and catecholborane. Thus, heating the borate **2** with borane−methyl sulfide in toluene to 100 °C (bath temperature) for 3 h provides clean catecholborane. The ^{11}B NMR showed the disappearance of the peak due to BMS at −20.2 ppm and the appearance of a new peak due to catecholborane at +28.2 ppm (doublet). It also showed some (10%) starting borate **2**. This may be due to some loss of borane due to the higher reaction temperature. Using a small excess of $Me_2S:BH_3$ reduces the amount of unreacted borate **2**; however, it could not be removed completely. However, the catecholborane prepared in this way was of better purity than the present commercial sample as observed by ^{11}B NMR.

Scheme 1

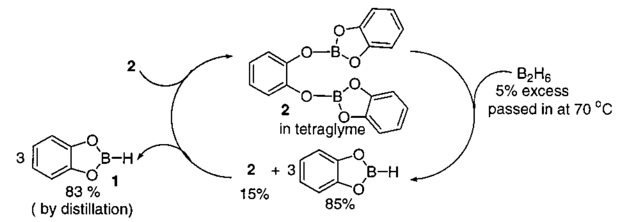
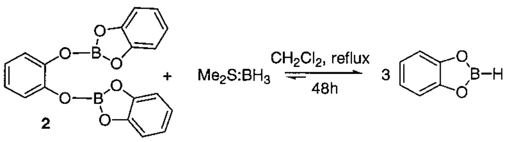


Table 1: **Preparation of catecholborane^a from borate 2 and $Me_2S:BH_3$ in various solvents**

reaction solvent	reaction conditions
toluene	90 °C/4 h
toluene	110 °C/2 h
dichloromethane	reflux/48 h
tetrahydrofuran	reflux/12 h
n-heptane	reflux/10 h
neat (no solvent)	102 °C/2 h

[a] Borate **2** (10 mmol) was added to the solvent, $Me_2S:BH_3$ (11 mmol) added, and the contents were slowly heated to the conditions mentioned above. The completion of catecholborane formation was established by ^{11}B NMR analysis.

To carry out the reaction at lower temperatures, the reaction was also tried in dichloromethane. Borane−methyl sulfide complex was added to the borate **2** in dichloromethane, and the contents were stirred further. Here also the equilibration was slow at room temperature but was accelerated considerably under reflux conditions. However, in dichloromethane, even under reflux conditions, the equilibration reaction required 48 h for the predominant formation of catecholborane.



(5)

Catecholborane was also prepared from the borate **2** and $Me_2S:BH_3$ in other solvents such as tetrahydrofuran and *n*-heptane and under neat conditions. Table 1 summarizes the results.

To obtain neat catecholborane, the solvent used as the reaction medium needs to be separated from the reaction mixture in all of these procedures. Unfortunately, in the case of high boiling solvents, such as toluene, *n*-heptane, and THF, considerable amounts of mixtures were obtained, since the boiling point of catecholborane is relatively low (bp 77 °C/100 mmHg). This problem was circumvented by treating the borate **2** with $Me_2S:BH_3$ without any solvent, heating the reaction mixture slowly to 102 °C, at which temperature the borate **2** melts and the dimethyl sulfide distills and is recovered. However, under these conditions a small amount of diborane gas escapes. Accordingly, a small excess (2−4%) of $Me_2S:BH_3$ is recommended. It is of interest to note that attempts to use a similar neat reaction with catechol and $Me_2S:BH_3$ gave poor results earlier[6] Apparently, borate **2** is more convenient for such preparations.

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(9) (a) Reference 2g, p 18. (b) Kanth, J. V. B.; Brown, H. C. *Inorg. Chem.* **2000**, *39*, 1795.

The catecholborane was also prepared using the borate **2** with other reactive borane−Lewis base complexes, such as THF:BH_3, *i*-Am_2S:BH_3, PhEtPr^{i}N:BH_3, $PhEt_2N$:BH_3, *i*-Pr_2-Bu^{i}N:BH_3 Et_3N:BH_3 and *i*-Pr_2EtN:BH_3 following procedures similar to that used for borate **2** and Me_2S:BH_3. Borane−tetrahydrofuran readily reacts with borate **2**, even at room temperature, and the catecholborane was obtained in 80% yield after the removal of volatile tetrahydrofuran. With the amine−borane complexes, the initial equilibration with borate **2** readily occurs at room temperature. However, the liberated amine from the amine−borane after this initial reaction complexes with the borate **2**, as observed by the ^{11}B NMR examination, which showed peaks corresponding to the formation of amine complexes of borate **2**, and this requires additional heating to achieve further reaction.

The catecholborane obtained after distillation using above-mentioned procedures has been stored at 0 °C, and no appreciable disproportionation was noted. However, when catecholborane was stored at room temperature, the amount of borate seemed to increase, similar to the observations made earlier.[2c]

In conclusion, we have developed new, economical, convenient, and environmentally benign procedures for the preparation of the valuable organoborane reagent, catecholborane, which is finding increasing application in organic synthesis. These procedures, which are free of problems, such as vigorous reaction and evolution of excess hydrogen, associated with the currently used procedure should encourage more practicing organic and organometallic chemists to use this versatile reagent.

Experimental Section

General. All manipulations and reactions with air-sensitive compounds were carried out in an inert atmosphere (dry nitrogen, argon, etc). The special techniques employed in handling air-sensitive materials are described elsewhere.[2g] The glassware was oven-dried for several hours, assembled while hot, and cooled in a stream of dry nitrogen gas. ^{11}B NMR spectra were recorded on a 300 MHz multinuclear instrument. The chemical shifts δ are in ppm relative to BF_3:OEt_2. Hydride analysis studies were carried out using the gasimeter. Triglyme and tetraglyme (anhydrous), catechol, Me_2S:BH_3 were procured from Aldrich; boric acid was obtained from (Mallinckrodt); all were used as obtained. All of the solvents, toluene, *n*-heptane, THF, and dichloromethane, were distilled prior to use.

Preparation of Tri-*O*-phenylene bis-borate (2). This was prepared closely following the literature procedure.[8b] An oven-dried RB flask provided with a septum inlet and a stirring bar fitted with Dean−Stark apparatus was charged with catechol (16.52 g, 150 mmol) and boric acid (6.18 g, 50 mmol) in toluene (50 mL). The contents were gently refluxed until all of the H_2O (5.4 g, 300 mmol) formed during the reaction had been collected in the Dean−Stark apparatus (∼3−4 h). The completion of reaction was also confirmed by ^{11}B NMR, which showed clean formation of borate **2** (+22.3 ppm, s), with no other boron species present. The solvent toluene was distilled-out to obtain borate **2** as a white solid (mp: 99−102 °C, lit.[8b] 97−103 °C) in quantitative yields.

Preparation of Catecholborane from the Borate 2 and Diborane Gas. An oven-dried RB flask provided with a septum inlet, stirring bar, and gas bubbler was assembled hot and cooled to room temperature under a stream of nitrogen. The gas bubbler was connected to a diborane generation set-up as described elsewhere.[9] The flask was charged with the borate **2** (17.31 g, 50 mmol) in a temperature bath that was kept at 100 °C. Diborane gas (40 mmol, excess), generated as described elsewhere, was passed into the reaction mixture slowly. The diborane gas was readily reacted with the borate **2**. The ^{11}B NMR examination showed clean formation of catecholborane in addition to a minor amount of unreacted borate **2** (10%). After the complete generation and absorption of diborane gas, the gas bubbler was removed, and the reaction flask was fitted with a distillation set-up. Distillation under reduced pressure (49 °C/50 mmHg, lit.[2f] 50 °C/50 mmHg) provided catecholborane in 80% yield (12.83 g) and in 98% chemical purity. The residue in the distillation flask was identified as the borate **2**, which can be mixed with further amounts of borate **2** and used again for the generation of catecholborane.

Preparation of Catecholborane from the Borate 2 and Diborane Gas in Toluene. The procedures followed for all solvents, such as toluene, *n*-heptane, tetralin, diphenyl ether, etc., were essentially the same, and the procedure followed using toluene as solvent is representative.

An oven-dried RB flask provided with a septum inlet, stirring bar, and gas bubbler was assembled hot and cooled to room temperature under a stream of nitrogen. The gas bubbler was connected to a diborane generation set-up as described elsewhere.[9] The flask was charged with the borate **2** (17.31 g, 50 mmol) in dry toluene (30 mL), and the reaction mixture was kept at 90 °C (bath temperature). Diborane gas (40 mmol, excess), generated as described elsewhere, was passed into the reaction mixture slowly, during 4 h. The diborane gas was slowly absorbed into the borate−toluene mixture. The ^{11}B NMR examination showed clean formation of the catecholborane in 86% yield in addition to a minor amount of unreacted borate **2** (14%).

Preparation of Catecholborane from the Borate 2 and Diborane Gas in a Glyme. The procedures followed in the glymes, such as di-, tri-, and tetraglyme, were essentially the same, and the procedure followed using tetraglyme as solvent is representative.

An oven-dried RB flask provided with a septum inlet, stirring bar, and gas bubbler was assembled hot and cooled to room temperature under a stream of nitrogen. The gas bubbler was connected to a diborane generation set-up as described elsewhere.[9] The flask was charged with the borate **2** (17.31 g, 50 mmol) in dry tetraglyme (30 mL), and the reaction mixture was kept at 70 °C. Diborane gas (30 mmol, small excess), generated as described elsewhere, was passed into the reaction mixture slowly. The diborane gas was readily absorbed into the borate−tetraglyme mixture. The ^{11}B NMR examination showed clean formation of catecholborane in addition to a minor amount of unreacted borate **2** (10%). After the complete generation and absorption of diborane gas, the gas bubbler was removed and the reaction flask was fitted with a distillation set-up. Distillation under reduced pressure provided catecholborane in 83% yield (13.32 g) and in 98% chemical purity. The residue in the distillation flask was identified as the borate **2** in tetraglyme, which can be mixed with further amounts of borate **2** and used again for the generation of catecholborane.

Preparation of Catecholborane from the Borate 2 and Borane−Lewis Base Complex without Solvent. The procedure followed with all the borane−Lewis base complexes, wherein the Lewis base could be an amine, dialkyl ether, or dialkyl sulfide, is essentially same. The following procedures are representative.

An oven-dried RB flask provided with a septum inlet, stirring bar, and a reflux condenser was assembled hot and cooled to room temperature under a stream of nitrogen. The flask was charged with the borate **2** (17.31 g, 50 mmol) and borane-methyl sulfide (5.0 mL, 10.2 M, 51 mmol). The reaction mixture was slowly heated to 100 °C for 1 h, by which time the ^{11}B NMR examination showed the disappearance of the peak due to borane−methyl sulfide complex (−20.2 ppm, q) and the appearance of a new peak due to catecholborane (+28.3 ppm, d). The liberated methyl sulfide was pumped-off, and the residue was distilled under reduced pressure to obtain catecholborane in 85% yield (13.64 g) and 97% chemical purity.

Preparation of Catecholborane from Borate 2 and THF:BH$_3$. An oven-dried RB flask provided with a septum inlet, stirring bar, and a reflux condenser was assembled hot and cooled to room temperature under a stream of nitrogen. The flask was charged with the borate **2** (17.31 g, 50 mmol), followed by THF:BH$_3$ (51 mL, 1.0 *M*, 51 mmol). The progress of the reaction was followed by ^{11}B NMR analysis of the reaction mixture. Initially, the reaction mixture was stirred at room temperature for 2 h, by which time 80% of the reaction is complete. The contents were then slowly heated to 50 °C (bath temperature), maintaining a constant pressure of dry nitrogen. It showed the disappearance of the peak due to the borane−THF complex (−0.2 ppm, q) and the appearance of a new peak due to catecholborane (+28.3 ppm, d, ∼90%). The reaction mixture also showed some amount of unreacted borate **2** (+22.3, s, ∼8%). Further heating did not improve the yield of catecholborane.

Preparation of Catecholborane from Borate 2 and Lewis Base−BH$_3$ in a Solvent. The procedure followed in all the solvents, such as tetrahydrofuran, hydrocarbon solvents with boiling point more than 50 °C, dichloromethane and with various borane−Lewis bases, wherein the Lewis base could be a cyclic ether, a dialkyl sulfide, or a tertiary amine, is the same. The following procedures are representative.

An oven-dried RB flask provided with a septum inlet, stirring bar, and a reflux condenser was assembled hot and cooled to room temperature under a stream of nitrogen. The flask was charged with the borate **2** (17.31 g, 50 mmol) in dry toluene followed by borane−methyl sulfide (5.0 mL, 10.2 M, 51 mmol). The contents were slowly heated to 100 °C (bath temperature), maintaining the constant pressure of dry nitrogen. The progress of the reaction was followed by ^{11}B NMR analysis of the reaction mixture. It showed the disappearance of the peak due to the borane−methyl sulfide complex (−20.4 ppm, q) and the appearance of a new peak due to catecholborane (+28.3 ppm, d, ∼90%). The reaction mixture also showed some amount of unreacted borate **2** (+22.3, s, ∼10%). Further refluxing did not improve the yield of catecholborane.

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