# Cyanide Sensing Using Three-Coordinate Borane Molecules

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ABSTRACT: With their high toxicity and use in industrial practices, cyanide has recently become the focus of detection strategies. One such strategy is based on the formation of a covalent bond between the cyanide anion and an electrophilic detector, in this case a three-coordinate borane. Unlike other detectors, these boranes are able to work in aqueous solutions and have a high affinity with cyanide. However, many are limited by their turn-off fluorescence response. Here, two borane complexes were synthesized with peripheral cationic groups and turn-on fluorescence capabilities and tested for cyanide-sensing. One was determined to detectably bind to cyanide at 26 parts per billion in aqueous solution, making it a strong sensor. This review will discuss photo-induced electron transfer, an important part of these detector systems, and explain it using molecular orbital theory.
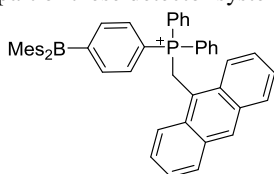
Figure 1: One of the three-coordinate boranes with potential turn-on fluorescence and a peripheral cationic charge, in this case, on the phosphorus, researched in this paper.

Introduction

The cyanide anion, CN^-, is an extremely toxic molecule, and long term exposure can lead to severe problems in the central nervous system.[1] Furthermore, it is used as part of a chemical defense system in many plants to protect against predation. Consumption of these cyanogenic plants, such as cassava, has recently increased and ignited interest in cyanide detection, particularly as animal studies suggest these plants may be correlated with fetal health issues.[1,2]

There have been several approaches to cyanide detection using chemical detectors. These systems involve the formation of covalent bonds between these detectors and the cyanide anion, due to its strong nucleophilic character.[3] However, many of the detectors are only usable in organic solutions and do not function in aqueous environments, severely limiting their practical capabilities.[3] Additionally, these methods use fluorescence and colorimetric sensors to detect the covalent bond formation, but finding a specific and sensitive sensor has proven difficult.[4] One additional problem is that many other anions, such as fluoride, bind to the sensor, interfering with their detection.[4] The last major problem is that detectors that are able to sense cyanide at physiologically lethal levels (> 20 μM) are rare.[4]
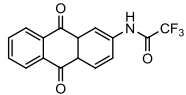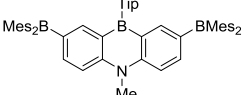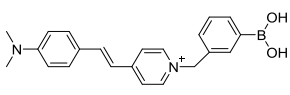
The sensors generally fall into one of two categories: electrophilic organic derivatives that form a covalent bond with the anion,[3] or Lewis acid derivatives that contain a metal or metalloid which covalently binds to the cyanide molecule.[4] Examples of both of these categories can be seen in Table 1. The organic derivatives often require basic pH and high cyanide levels, but the metal-containing molecules do not have these issues. This is due to the low energy of their filled bonding orbitals and thus, the metal complexes are more flexible sensors.[2,8] In particular, one class of metalloid sensors that has shown potential are borane compounds with peripheral cationic groups.[2,5,6] Neutral borane complexes detect poorly in aqueous solutions, but the presence of peripheral cationic groups, such as the pyridine seen in

Figure 2, rectifies this issue due to the increased hydrophilicity.[3] A number of complexes incorporating these cationic groups have been studied but they remain limited by their turn-off fluorescence response, where binding to the cyanide causes a decrease in the fluorescence intensity.[2] This is disadvantageous, as it limits the amount of cyanide that can be detected and the presence of other moieties absorbing in nearby regions interferes with the concentration calculations.
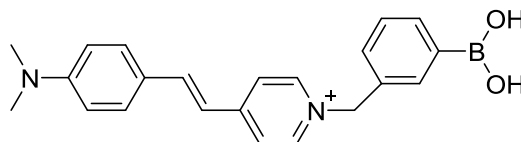

Figure 2: An example of a borane which contains a peripheral cationic group, in this case, the substituted pyridine. The boron atom covalently binds to the cyanide anion to form a complex which can then be detected. [6]

Thus, a current topic of investigation in cyanide sensing is synthesizing a borane molecule that incorporates these peripheral cationic groups while also offering a *turn-on* fluorescence response, where binding to the cyanide increases the intensity of the fluorescence spectrum. As such, two possible molecules believed to have this turn-on response were synthesized and tested for their cyanide detection capabilities. The authors aim to find molecules that retain the advantages of other peripherally-cationic boranes while eliminating the turn-off response, as summarized in Table 1.

	Electrophillic Organic Derivatives	Lewis Acid Derivatives	
		Neutral Borane	Peripherally-Cationic Borane
Structure Example			
Advantages	- Functions in water	- Functions in biological pH - Low detection limits	- Functions well in water - Works at biological pH - Low detection limit
Disadvantages	- Requires basic pH - Requires high CN concentration	- Detects poorly in water due to insolubility	- Turn-off response
Source	[9]	[10]	[6]

Table 1: Previous sensors that have been used to detect the cyanide anion in solutions, as well as the advantages and disadvantages associated with them.
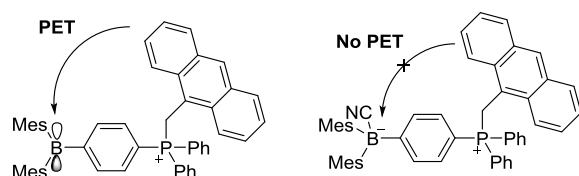

Figure 3: When **[1]**, the borane molecule, is not bound to the cyanide anion (left), the boron is able to receive electrons from the fluorophore electron donor, the anthryl moiety, through PET. Upon formation of the cyanoboranate (right), however, PET can no longer occur, as boron no longer has an empty p-orbital.

Key Theory from Inorganic Chemistry

Molecular orbital (MO) theory can be used to explain the electron configuration of the studied complexes' borane moiety (as seen in Figure 1), which lets us understand the fluorescence spectrum. When peripheral moieties of these molecules absorb energy to raise an electron to its excited state, this electron then transfers to the boron's empty p-orbital in a process known as photo-induced electron transfer (PET). However, upon the formation of a bond between the borane and the cyanide anion, PET is not observed, as shown in Figure 3.

Using MO theory, we can establish why a three-coordinate boron molecule can accept electrons, while a four-coordinate boronate cannot. To demonstrate this, molecular orbital diagrams of BH_3 and BH_4^- have been drawn, modeling the peripheral-cationic borane (Figure 4) and the cyanoboranate (Figure 5). As Figure 4 demonstrates, one of boron's p-orbitals is not involved in bonding interactions. Upon excitation of a peripheral group, which contains the molecule's HOMO, an electron is raised to an energy higher than the boron's p-orbital. This electron can then relax by transferring to the p-orbital, the molecule's LUMO, through PET, as seen in Figure 4. As Figure 5 shows, however, the formation of a fourth bond to the boron leaves no empty p-orbital for electrons from the excited fluorophore to transfer to. This inhibits the PET of the system and the electron must remain in the peripheral group, which now contains the molecule's LUMO.
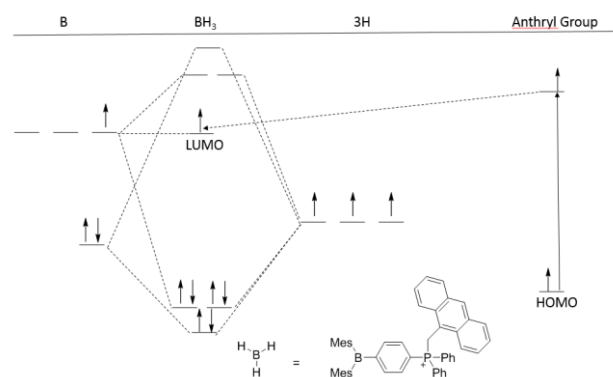

Figure 4: An MO diagram of BH_3, a simple three-coordinate boron, similar to **[1]**[+] studied in Kim et al.[2] The anthryl group acts as an electron donor, giving its electrons to the boron, the electron acceptor, through PET.
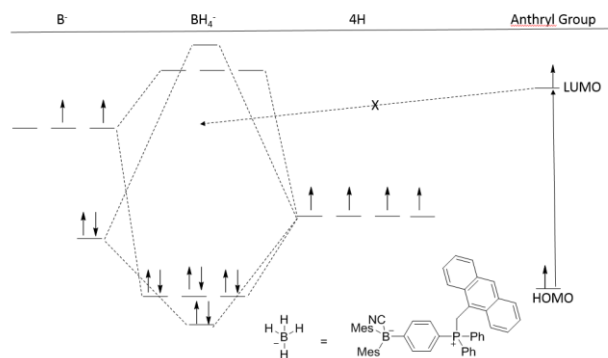
Figure 5: An MO of BH_4^-, a simple four-coordinate boronate, similar to **[1]**CN, generated upon bond formation between the cationic sensor and the cyanide anion. Without the empty p-orbital of the boron, the anthryl group cannot donate its electron to the boronate.

Synthesis of two molecules believed to have turn-on fluorescence, referred to as **[1]** and **[2]**, was performed by combining *p*-Ph$_2$P-C$_6$H$_4$-BMes$_2$ (Mes = mesityl) with 9-bromomethyl anthracene or *N*-(3-bromo-propyl) dansylamide and heating to reflux to form **[1]** and **[2]**, respectively (see Figure 6). Yields were 82% for **[1]**Br and 40% for **[2]**I. There two molecules differ by a single group: **[1]** has an anthryl group, while **[2]** has a dansyl group, as noted in Figure 6. These two groups act as the fluorophore for their respective molecules, where they are excited by fluorescence to reach a higher energy state.
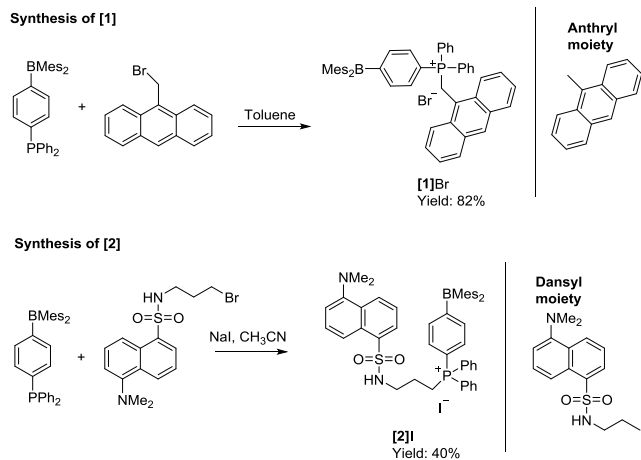

Figure 6: Reactions used to synthesize **[1]**Br (top) and **[2]**I (bottom), the two subjects of investigation in this review. The single difference in these molecules is the identity of a peripheral group; anthryl for **[1]** and dansyl for **[2]**.

Next, to confirm that the boron on these molecules could bind to the cyanide anion, **[1]** and **[2]** were put into a mixture of methanol. It was found that solids precipitated upon the addition of KCN. Next, it was confirmed with NMR (^{1}H, ^{13}C, ^{31}P and ^{11}B) and IR spectroscopy that these complexes indeed contained a covalent bond between the cyano group and the borane. Upon addition of B(C$_6$F$_5$)$_3$ to CDCl$_3$ solutions of **[1**(CN)**]** and **[2**(CN)**]**, **[1]**$^+$ and **[2]**$^+$ regenerated, indicating that the bonding process was reversible.

The boranes were then analyzed using fluorescence spectroscopy to characterize their absorption peaks, in order to determine their detection capabilities. Peaks at 340 nm for **[1]**Br and 335 nm for **[2]**I were assigned to triarylboron moiety, based on the similarity between these peaks and those in simple boranes.[7] Furthermore, there are weak absorbances at 427 nm (for **[1]**$^+$) and 501 nm (for **[2]**$^+$), which were assigned to the anthryl group of **[1]**$^+$ and the dansyl group of **[2]**$^+$, again based on comparison to simple boranes. As seen in Figures 7 and 8, upon the addition of the cyanide anion, the peaks at 340 and 335 nm decrease in intensity, while the peaks at 427 and 501 nm become stronger. The fact that the intensity of the anthryl or dansyl groups' fluorescence becomes stronger upon formation of the cyanoboranate

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[a] Unless otherwise noted, all data and analysis in this section comes from Kim et al[2].

means that these molecules have a turn-on fluorescence response to the cyanide's presence. This indicates that a major goal of the authors, to synthesize boranes with peripheral cationic groups and a turn-on response to bonding to cyanide, was successful.
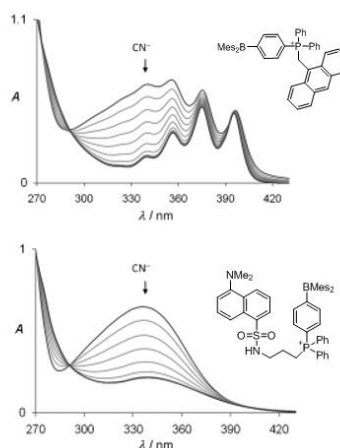
Figure 7: UV-Vis spectra ranging from 270 to 420 nm, of **[1]**$^+$ (top) and **[2]**$^+$ (bottom), showing the absorption from the triaryl borane moiety; as the cyanide anion is present in increasing concentrations, the intensity decreases. Spectra taken from Kim et al[2].
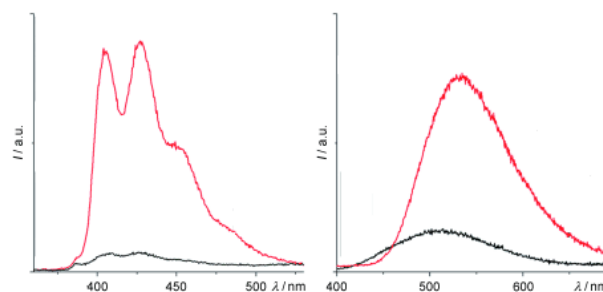
Figure 8: UV-Vis spectra demonstrating the absorption due to the anthryl group of **[1]**$^+$ (left, black) and the dansyl group of **[2]**$^+$ (right, black). Upon bond formation with the cyanide anion, the intensity increases (red). Spectra taken from Kim et al[2].

Based on the quenching of fluorescence in the triaryl groups and increase in intensity in the peripheral groups of **[1]**$^+$ and **[2]**$^+$, it was suggested that PET was occurring. In this process, the excited fluorophore transfers electrons to the electron-deficient borane moiety, which has an empty p-orbital in its three-coordinate state, as discussed above. This explains the borane's high intensity and the anthryl and dansyl groups' weak intensities. Upon formation of the cyanoboranate, however, the boranate moiety's p-orbital is filled and it can no longer accept electrons from the fluorophores, thus inhibiting the PET. This results in the decrease in the intensity of the boranate moiety, as demonstrated in Figure 7, and an increase in intensity of the fluorophore, as seen in Figure 8.

Next, the cyanide binding constants of **[1]**$^+$ and **[2]**$^+$ were determined by UV-Vis titration experiments, as seen in Figure 7. For these molecules to act as suitable cyanide sensors, they must be able to form strong bonds to the anion. Known amounts of cyanide were added to a solution containing the boranes and the

decrease in intensity was measured. These results give a binding constant of at least 10^6 M^{-1}, which indicates strong bonding between the atoms. However complete quenching could not be observed due to other absorbances in the region, and a more accurate constant could not be determined. Previous results have indicated that similar borane molecules also have strong binding constants with fluoride anions, so a similar experiment was carried out to determine how selective these sensors are. The fluoride binding constants were much weaker, roughly 340 M^{-1} for **[1]**$^+$ and 500 M^{-1} for **[2]**$^+$, indicating that these boranes prefer the cyanide anion. In addition, similar experiments showed that these cations showed no preference for a variety of other anions, such as Cl$^-$, Br$^-$, NO$_3^-$, SO$_4^-$ among others, demonstrating that these boranes are highly selective for cyanide anions.

The next step to determine the sensing abilities of these borane molecules was to test their capabilities in aqueous solutions at neutral pH. **[1]**$^+$ was found to decompose in a mixture of H$_2$O and MeOH, meaning that it cannot be a cyanide detector in aqueous solutions. **[2]**$^+$, on the other hand, was found to be stable at a neutral pH in the same solution. Furthermore, **[2]**$^+$ was found to be able to detect cyanide at very low concentrations in these aqueous solutions, as shown in Figure 9. It can detect cyanide concentrations as low as 26 parts-per-billion (ppb, 26 μM), thus making it one of the most sensitive cyanide sensors yet studied.
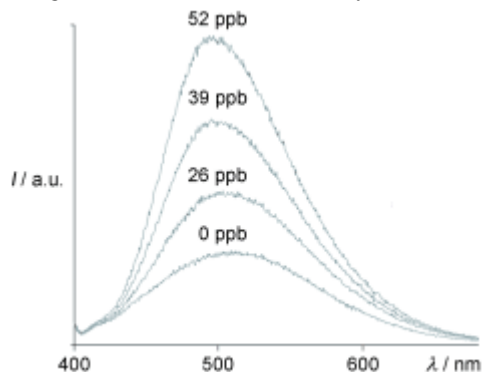
Figure 9: A fluorescence spectrum of the dansyl absorbance of **[2]**$^+$ in mixture of H$_2$O/MeOH at pH 7. As increasing amounts of cyanide are added, the intensity also increases. Even at concentrations as low as 26 ppb, this increase is still easily detectable. Spectrum taken from Kim et al.[2]

These results indicate that **[2]** retains the main advantages of peripherally cationic boranes, namely their ability to work in aqueous solutions at neutral pH to detect low concentrations, while eliminating their main disadvantage. **[2]** thus represents an important step forward in cyanide detection using peripherally cationic boranes.

It is worth noting that the authors did not test the capabilities of **[2]** with a biological matrix or discuss the possibility of them being compatible. As a cyanide detector capable of functioning in a biological matrix (the non-cyano parts of a biological system) has been observed, the work done here does not represent the most advanced detector yet.[11] This is particularly important due to the strong interest in methods that can detect cyanide in plants: if these borane complexes were to actually be used for this purpose, then the ability to do so in biological matrices is imperative. The detector that was able to detect cyanide directly from a biological matrix, namely a freshly cut cassava, was a Co(III) complex, where binding to the cyanide anion displaces an H$_2$O ligand.[11] This ligand displacement method is an approach

that has not been attempted with boron complexes and based on the success of this Co(III) detector, may be an avenue worth pursuing.

Another aspect not considered by this paper is the possibility of binding to the hydroxide ion, $^-$OH. It has been noted that the -BMes$_2$, such as the ones researched here, often have a competing response from hydroxide ions.[12] The effects of $^-$OH binding can significantly affect the range of pHs in which a detector functions and must be considered in practical applications, such as testing drinking water. Neither the effects of pH nor the possibility of binding to hydroxide were discussed at all in this paper. Thus, while this paper represents a step forward for borane-based cyanide detectors, there nonetheless remain questions that should be answered. As this paper does not consider possible practical applications, such as detection on a biological matrix or drinking water, the actual use of these molecules remains unknown.

Conclusion

The authors have successfully synthesized a molecule that retains the advantages of peripherally cationic boranes while getting rid of their major weakness, their turn-off fluorescence. When the peripheral dansyl group on **[2]** is excited, it transfers electrons to the triarylboron, which is not possible in **[2]**CN, as explained with MO diagrams. This makes the dansyl group fluorescence upon formation of the cyanide complex, without the signal being present in the unbound borane. This represents a significant step forward for the study of borane cyanide detectors, though more advanced groups of sensors still outperform these molecules and their practical application remains unstudied.

AUTHOR INFORMATION

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