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Published in:  
Computational and Theoretical Chemistry

DOI:  
10.1016/j.comptc.2017.02.001

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Document Version  
Final author's version (accepted by publisher, after peer review)

Publication date:  
2017

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):  

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Bonding in $B_2$ and $B_2^+$: insights from full configuration interaction and valence bond studies

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Keywords: $B_2$, $B_2^+$, valence bond theory, full CI, ab initio calculations

Highlights:

1) two $\sigma$ and two $\pi$ bonds are responsible for the bonding in $B_2$

2) $B_2$ possesses two different kinds of $\sigma$ bonds: a strong, short bond and a longer, weak bond

3) In $B_2^+$, no $\pi$ bond exists, only two $\sigma$ bonds
Graphical Abstract:

![Graphical Abstract Image]

**Abstract:** Full Configuration Interaction (Full-CI) and Valence Bond Self-Consistent Field (VBSCF) methods have been used to study the electronic structure and bonding in $B_2$ and $B_2^+$ molecules. The bonding analysis based on these calculations shows that the $B_2$ molecule is stabilised due to the formation of a double $\sigma$ bond, one strong $\sigma$-bond together with one second weaker $\sigma$-bond, and two weak $\pi$ bonds. Upon ionisation one $\pi$ electron is removed from the system and $B_2^+$ is formed, which has a one electron $\sigma$ bond, instead of a $\pi$ bond. It has been shown that a few carefully chosen VB configurations are enough to describe the bonding; with these structures, geometrical parameters as well as dissociation energies of these unusual molecular species are in agreement with full-CI results.
Introduction

The description of bonding in small molecules remains a challenge: although for simple diatomic molecules chemical bonding seems clear, the situation in $C_2$ showed that it can still lead to surprises [1-7]. Several theoretical studies, at various levels of theory, have been devoted to describe the chemical bonding in the $C_2$ molecule. There is, however, still an on-going debate within the chemical community regarding the bond-order in this molecule. Considering the carbon-carbon bond length and the relaxed force constant, $C_2$ fits in between the molecules containing double and triple C-C bonds, i.e., ethene and ethyne [4,8]. On the other hand, analyses based on full configuration interaction and valence bond calculations [2] and that based on natural orbital functional theory (NOFT) [9] have shown that $C_2$ and its isoelectronic species (CN+, BN and CB-) all possess quadruple bond: a normal $\sigma$ bond, two $\pi$ bonds and one long, weaker, $\sigma$ bond.

Another molecule that may show similar behaviour, as $C_2$, is the $B_2$ molecule. According to a molecular orbital scheme, the valence electronic configuration would be $2\sigma_g^22\sigma_u^21\pi_u^2$ and it would have a triplet ground state. The bond order according to this model would be 1, as the $\sigma$ electrons would not contribute to the bonding. Only the two $\pi$ electrons in the $\pi_u$ orbitals would contribute to the bonding. This situation is similar to the $C_2$ case, except that in $B_2$ the $\pi_u$ orbitals are half filled, leading to an even weaker $\pi$ bond than in the $C_2$ case.

In this report, we study the nature of the bonding in $B_2$ using full configuration interaction calculations and valence bond calculations, to see if there are similarities in the $\sigma$ bonding situation to $C_2$. We also study the bonding in the
ionised $B_2^+$ and $B_2^{2+}$ species, to elucidate the nature of the chemical bonding with only one or no bonding $\pi$ electrons.

**Computational details**

In all calculations, the cc-pVDZ basis set was used. The full CI calculations were performed using GAMESS-UK [10]. Both 1s orbitals were kept frozen. Initial orbitals were taken from a preceding full valence MCSCF calculation.

The valence bond (VBSCF [11,12]) calculations were performed with TURTLE [13] as implemented in GAMESS-UK. Strictly atomic VB calculations were performed where the orbitals were kept strictly atomic, and delocal VB calculations were performed in which the orbitals were allowed to delocalise [14].

**Results and discussion**

*Full Configuration Interaction calculations on $B_2$, $B_2^+$ and $B_2^{2+}$*

According to the full CI calculations, the ground state of $B_2$ is a triplet with a leading valence electronic configuration $2\sigma_g^22\sigma_u^21\pi_{ux}^11\pi_{uy}^1$. At the equilibrium distance of 1.632 Å (Table 1), the weight of this configuration is 76.6%. The next leading configuration with a weight of 9.5% is $2\sigma_g^21\pi_{ux}^11\pi_{uy}^13\sigma_g^2$, in which the two electrons from the antibonding $2\sigma_u$ orbital are excited to the bonding $3\sigma_g$ orbital.
Ionization of B\textsubscript{2} leads to a wavefunction with a 84.0\% weight for the 2\(\sigma_g^2\)2\(\sigma_u^2\)3\(\sigma_g^1\) configuration. Note that upon ionization, the lowest configuration has no \(\pi\) electrons anymore, and one electron occupies the bonding 3\(\sigma_g\) orbital. As expected, the dissociation energy becomes lower, and the bond distance increases with respect to that of neutral B\textsubscript{2} (Table 1). Further ionization to B\textsubscript{2}\textsuperscript{2+} does not lead to a bonded species, and spontaneous dissociation occurs.

The full CI calculations are indicative that the bonding situation in B\textsubscript{2} is unusual and shows agreement with the bonding situation in for example C\textsubscript{2}. A closer analysis of the bonding using valence bond calculations is presented in the next section.

**Table 1.** The full CI dissociation energies (kcal/mol), equilibrium distance (Å), and total energy (Hartree) for B\textsubscript{2}, and B\textsubscript{2}\textsuperscript{+}.

<table>
<thead>
<tr>
<th>Molecule</th>
<th>(E_{\text{dis}})</th>
<th>(R)</th>
<th>(E_{\text{tot}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>B\textsubscript{2}</td>
<td>59.57</td>
<td>1.632</td>
<td>-49.274884</td>
</tr>
<tr>
<td>B\textsubscript{2}\textsuperscript{+}</td>
<td>42.63</td>
<td>2.195</td>
<td>-48.951664</td>
</tr>
</tbody>
</table>

**Valence Bond calculations on B\textsubscript{2} and B\textsubscript{2}\textsuperscript{+}**

At first, a valence bond calculation was performed with the bonding situation with two electrons in each boron-2s orbital and one electron in the \(\pi_x\) and one electron in the \(\pi_y\) orbitals (VB-1, Figure 1). In total, six structures were used. The energy as a function of the B-B distance is plotted in Figure 2 (VB-1). As can be seen, no minima can be found using these structures, and the \(\pi\)-bonds alone in
the bonding $\pi_u$ orbitals are not capable of keeping the atoms together: the nonbonding electrons repel too much to form a stable molecule.

**Figure 1.** Different structures considered in the valence bond calculations.

**Figure 2.** Dissociation curves for $B_2$, calculated using different valence bond models and full-Cl (see text).
A minimum in the potential energy curve (VB-2, Figure 2) is obtained when structures are added that describe two $\sigma$ bonds between the two boron atoms (VB-2, Figure 1). Using this (12-configuration) VB wavefunction, the calculated dissociation energy is 44.9 kcal/mol, which is only in fair agreement with the full CI dissociation energy (Table 1, and Figure 2). Correlation in $B_2$ is apparently extremely important to describe the bonding situation accurately. The atomic orbitals involved in these $\sigma$ bonds are the s and $p_z$ orbitals of each boron atom (Figure 3). One strong bond is formed between VB orbitals (1) and (8) with an overlap of 0.77, and one weaker bond is formed between VB orbitals (2) and (7) with an overlap of only 0.09. The VB orbitals (3), (4), (5), and (6) form two $\pi$ bonds; the overlap between the p orbitals is 0.40.

Figure 3. The strictly atomic valence bond orbitals involved in the bonding.

To improve the quality of the VB wavefunction in VB-local, fourteen more configurations were included in the calculation (VB-3 in Figure 2). Ten of these
have one doubly occupied valence orbital (either orbital 2s or 2p\textsubscript{z}) on either of the two B atoms and four configurations have two doubly occupied orbitals (2s on one atom and 2p\textsubscript{z} on the other atom). With this (26-configuration) wavefunction, the calculated dissociation energy is 56.65 kcal/mol, which is in very good agreement with the full CI dissociation energy. The equilibrium bond distance is 1.595 Å. At this bond distance, all 26 configurations contribute to the wavefunction. The most important are those, which describe two \(\sigma\) bonds between the two boron atoms. The combined weight of these configurations is 38%. The second in importance are those, which describe two doubly occupied orbitals; their accumulated weight in the wavefunction is 34%. The remaining 28% consists of those configurations, which have one doubly occupied valence orbital on one of the two boron atoms. The general bonding picture of this more accurate wavefunction is similar to the simpler VB-2 description.

Using the delocal model, the dissociation curves have been calculated. The dissociation energy obtained using the 12-configurations wavefunction (VB-4, Figure 2) is 52.9 kcal/mol, which is substantially better than the dissociation energy obtained using the strictly atomic VB-2 model with the same number of configurations. A similar bonding picture is obtained: the wavefunction consists mainly of only one structure describing one strong \(\sigma\) bond between the valence bond orbitals (5d) and (6d) (Figure 4), with an overlap of 0.86, and another weaker \(\sigma\) bond between the orbitals (1d) and (2d) (Figure 4). These orbitals have an overlap of 0.29. Note that the overlap has increased significantly in comparison to the overlap obtained with the strictly atomic model. The two \(\pi_{a}\) orbitals are both occupied with one electron each.
The dissociation energy calculated using 26-configuration wavefunction (VB-5, Figure 2) in VB-delocal is 59.60 kcal/mol, which is very close to that obtained with the full CI calculations. The equilibrium bond distance calculated using this wavefunction is 1.606 Å, which is also in excellent agreement with that calculated using Full CI. This wavefunction gives a very accurate description, in line with the Full-CI results, but the main bonding features are already captured by the simpler 12-configuration VB wavefunction. For comparison, a full valence CASSCF calculation (CASSCF(6,8)) yields a dissociation energy of 59.74 kcal/mol. Smaller active spaces are not well-suited to describe this dissociation. Spin-coupled VB will also give similar results as it is in essence the same as VBSCF, but the latter method is more general.

The valence bond orbitals calculated in the strictly atomic model for B$_2^+$ are depicted in Figure 5. In the VB wavefunction, several structures are important: the two main structures with a combined weight of 0.51 describe one doubly occupied 2s orbital (either orbital (1p) or (2p), Figure 5), a doubly occupied σ bond formed by the orbitals (1p-4p) or (2p-3p), and a singly occupied (3p)/(4p)
orbital. The two orbitals involved in the bonding have a small overlap of only 0.01. The next two structures with a combined weight of 0.46 describe two doubly occupied 2s orbitals ((1p) and (2p)) and a singly occupied (3p)/(4p) orbital. The calculated dissociation energy is 40.7 kcal/mol, which is in good agreement with the full CI results (Table 1).

Figure 5. The strictly atomic valence bond orbitals involved in the bonding of $\text{B}_2^+$. 

Conclusions

This study shows that unusual $\sigma$ bonding motifs exists in $\text{B}_2$ and $\text{B}_2^+$. In $\text{B}_2$, a double $\sigma$ bond is formed, of which one is a strong, regular, bond, while the second bond is weaker. Upon ionisation, one $\pi$ electron is removed from the system, while the other $\pi$ electron prefers to be in a $\sigma$ orbital. Also in this case, an unconventional $\sigma$ bond is formed.

Acknowledgement

RWAH acknowledges fruitful discussions with Prof. Dr. R. Broer (University of Groningen).
References


