**π-Bonding in Inorganic Systems**

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**ABSTRACT**

Evidence from nuclear magnetic resonance studies for π-bonding between boron and nitrogen in the boranes is presented. Preliminary experiments, by infrared spectroscopy, which indicate that a similar situation might exist between phosphorus (III) and nitrogen, in open chain compounds, are also reported.

The energy barrier to rotation about the BN bond in dimethylaminophenylchloroborane is calculated (from four different observations on the N.M.R. spectra) as 13 ± 2 kca ls. Exploratory measurements on certain boron-oxygen compounds are also presented.

**INTRODUCTION**

It has been suggested that the search for monomers, suitable as intermediates in the synthesis of inorganic polymers, might well be pursued among those inorganic compounds in which a high degree of π-bonding occurs.

The borazines, (I), i.e. open-chain compounds in which both boron and nitrogen are three co-ordinate, are isoelectronic and isosteric with the corresponding olefins, (II). This point is particularly emphasized by the canonical form (Ia).

\[
\begin{align*}
\text{Ia:} & \quad B - \equiv N \\
\text{Ib:} & \quad B = \equiv N \\
\text{II:} & \quad C = C
\end{align*}
\]

Much circumstantial experimental evidence for the occurrence of π-bonding in the borazines is available (see ref. 1 and references cited therein) and it seemed likely that more direct evidence for the phenomenon could be obtained from nuclear magnetic resonance data and especially from studies on energy barriers to rotation.

Results of \(^1\)H nuclear magnetic resonance experiments on methylphenylaminodimethylborane, \(\text{C}_8\text{H}_8\text{NCH}_{3}\text{B(CH}_3)_2\), and phenyldimethylaminochloroborane, \(\text{C}_8\text{H}_8\text{BClN(CH}_3)_2\), have been
$^1$H Spectra of Phenylmethylaminochloroformate at Several Temperatures (a) 23°, (b) 93°, (c) 103°, (d) 109°, (e) 119°, (f) 137°.

Spectra were recorded at 40 MHz, Absorption occurred at γ-0.12

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published. These results confirm that a high barrier to rotation (estimated at 15 ± 3 kcal/s in the former and 18 ± 2 kcal/s in the latter) exists between boron and nitrogen and we have shown in a preliminary way, by comparing PhB(Cl)NMe₉₂ and PhB(NMe₉)₂, that the high barrier in the former is essentially due to π-bonding and not to steric considerations. Our evidence will be elaborated upon in this paper.

DISCUSSION

1. THE BORON-NITROGEN SYSTEM

In the borazenes a "partial" double bond, due to delocalization of π-type nitrogen electrons into a vacant π*-type boron orbital, is to be expected. The ¹H nuclear magnetic resonance spectrum of the compound phenyl(dimethylamino)chloroborane, C₆H₅NMe₂, showed a doublet at ν = 7.2 (fig. la.) attributed to methyl absorption, the occurrence of a doublet being consistent with the presence of two sets of protons in chemically-different and equally-abundant environments (cis- or trans- to the phenyl group). At progressively higher temperatures band broadening and decrease of maxima separation were observed (fig. 1b - 1d.), and at about 118° the doublet structure collapsed into a single broad band. At still higher temperatures the single band became increasingly narrow (fig. 1e, 1f.). The association of this kind of spectral behaviour with variable isomeric inter-conversion is well-established.¹

From observations on the recorded spectra, a value of 18 ± 2 kcal/s has been calculated for the energy barrier to rotation about the BN bond.

The ¹H nuclear magnetic resonance spectrum of bis-(N,N-dimethylamino)phenylborane, C₆H₅NMe₂, showed no splitting of the methyl absorption at room temperature and this is taken to indicate that the energy barrier to rotation about the BN bond in this compound is rather low, probably less than 10 kcal/s. Similar observations were also made on bis(N-methyl-amino)phenylborane, C₆H₅B(NMe₂)₂, (III).

Steric effects with respect to rotation about the BN bond would undoubtedly be greater in compound (II) (and III) than in (I). The presence of a lower barrier in (II), where back donation from two nitrogen atoms can occur, proves that the restriction to rotation in (I), where the boron atom is linked to a single nitrogen, must be due to electronic effects (i.e., π-bonding) rather than to steric factors. Furthermore these

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### TABLE 1.

<table>
<thead>
<tr>
<th>Compound</th>
<th>S.P. °C/mm.</th>
<th>nD</th>
<th>Method of Synthesis</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. PhBClMe₂</td>
<td>75/2</td>
<td>1.53202</td>
<td>PhBCl₂ + Me₂NH → PhBClMe₂ + Et₃N·HCl</td>
<td>10</td>
</tr>
<tr>
<td>II. Ph(NMe₂)₂</td>
<td>60/0.4</td>
<td>1.51684</td>
<td>PhBCl₂ + 4Me₂NH → Ph(NMe₂)₂ + 2Me₂NH·HCl</td>
<td>-</td>
</tr>
<tr>
<td>III. Ph(NHMe)₂</td>
<td>86/3</td>
<td>1.52902</td>
<td>PhBCl₂ + 4MeNH₂ → Ph(NHMe)₂ + 2MeNH₂·HCl</td>
<td>-</td>
</tr>
<tr>
<td>IV. PhBClNMePh</td>
<td>102/0.2</td>
<td>1.58774</td>
<td>PhBCl₂ + PhNMeN → PhBClNMePh + Et₃N·HCl</td>
<td>10</td>
</tr>
<tr>
<td>V. PhBClNMe⁺Pr</td>
<td>90/2</td>
<td>1.51932</td>
<td>PhBCl₂ + MeNH⁺Pr → PhBClNMe⁺Pr + Et₃N·HCl</td>
<td>-</td>
</tr>
<tr>
<td>VI. PhBClNMeEt</td>
<td>82/0.8</td>
<td>1.52844</td>
<td>PhBCl₂ + MeNHe → PhBClNMeEt + Et₃N·HCl</td>
<td>-</td>
</tr>
<tr>
<td>VII. PhBBrNMe₂⁺</td>
<td>63/0.8</td>
<td>PhBBr₂ + PhB(NMe₂)₂ → 2PhBBrNMe₂⁺</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>VIII. PhBF₃NMe₂⁺</td>
<td>62/3</td>
<td>1.50581</td>
<td>3PhBClNMe₂ + 3SbF₃ → 3PhBF₃NMe₂ + 3SbCl₃</td>
<td>-</td>
</tr>
<tr>
<td>IX. PhBClOMe⁺</td>
<td>57/7</td>
<td>1.51110</td>
<td>PhBCl₂ + Ph(OME)₂ → 2PhClOMe</td>
<td>11</td>
</tr>
<tr>
<td>X. PhB(OME)₂</td>
<td>45/3</td>
<td>1.49599</td>
<td>PhBCl₂ + 2MeOH → PhB(OME)₂ + 2HCl</td>
<td>11</td>
</tr>
<tr>
<td>XI. PhPClNMe₂</td>
<td>80/0.1</td>
<td>1.57510</td>
<td>PhPCl₂ + Me₂NH → PhPClNMe₂ + Et₃N·HCl</td>
<td>-</td>
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<tr>
<td>XII. PhP(NMe₂)₂</td>
<td>58/0.1</td>
<td>1.54791</td>
<td>PhPCl₂ + 4Me₂NH → PhP(NMe₂)₂ + 2Me₂NH·HCl</td>
<td>-</td>
</tr>
</tbody>
</table>

* Not yet completely analysed.
results show that cis/trans isomerism due to restricted rotation about inorganic atomic pairs, can be extended beyond the only hitherto established case of \( N = N \).

Further investigations into the borazene system have been based upon the compounds IV - VII (Table 1). The spectrum of compound IV, methylphenylaminophenylchloroborane, \( \text{C}_6\text{H}_5\text{BCl(CH}_3\text{NCH}_3\text{H})_2 \), showed no splitting of the methyl resonance in the range 25 - 200°, and this may be due to a high barrier to rotation about the BN bond, mainly for steric reasons, and a steric preference for the less hindered isomer. Likewise, aryl-substituted amides (e.g. \( \text{N}_3\text{HC}\text{H}_2\text{CNCH}_3\text{H} \)) show a single methyl resonance whereas \( \text{N}_3\text{H} \text{-dimethylamides show a doublet, and it has been suggested that at least 10\% of the less-favoured isomer is required to give a recognisable signal. Chemical and spectroscopic evidence for steric hindrance in the borazenes, particularly in the \( \text{N}_3\text{-aryl derivatives, is available.} \)

The spectra of the remaining compounds have only recently been recorded.

2. THE BORON-OXYGEN SYSTEM

Thermochromic and spectroscopic evidence shows that although a B-O bond has some double bond character, the ability to form \( \pi \)-bonds with boron is greater for nitrogen than oxygen.

In order to investigate this further, we have synthesised samples of the esters chloromethoxyphenylborane, \( \text{C}_6\text{H}_5\text{BCl(OCH}_3\text{H})_2 \), (II), and dimethoxyphenylborane, \( \text{C}_6\text{H}_5\text{B(OCH}_3\text{H})_2 \), (I).

The magnetic resonance spectrum of these compounds recorded at 60 Mc/sec (room temperature) reveals, in both cases, a broad low field signal characteristic of the phenyl group, together with a single line at somewhat higher field which is attributable to the methyl group resonance.

This section of the work is being continued.

3. THE PHOSPHORUS(II)-NITROGEN SYSTEM

\( \pi \)-Bonding in the phosphorus nitrogen bond has been invoked in the discussion of a FN compound and its suggested pseudoaromaticity. Spectroscopic investigations into the three co-ordinate phosphorus nitrogen system have therefore been undertaken.

The infrared spectrum of \( \text{N}_3\text{H} \text{-dimethyl-P-phenylphosphonimidyl chloride, C}_6\text{H}_5\text{PCH}_3\text{NCH}_3\text{H} \), (II), shows a medium band in the 1600 cm\(^{-1}\) region, characteristic of monosubstituted aromatic compounds. This is accompanied by another band at approximately 20 cm\(^{-1}\) lower and this may be due to the presence of an
unsaturated side chain which allows extended conjugation with the aromatic ring. Similar features have been observed in the spectra of borazines.\(^1\) It is significant that the low intensity band is absent in \(\text{H}_{10}\text{H}^2\text{N}^2\text{N}^3\text{N}^4\text{N}^5\text{N}^6\text{N}^7\)tetramethyl-2-phenylphosphonic diamide, \(\text{C}_6\text{H}_5\text{P}(\text{NMe}_2)^2\), (XII), where the extent of \(\pi\)-bonding would be expected to be reduced.

The \(^1\)H nuclear magnetic resonance spectra of these compounds recorded at 60 Mc/sec, are both characterised by a broad low field band, attributed to phenyl group resonance, and a doublet at higher field. This doublet was shown to arise from spin-spin interaction between the phosphorus and hydrogen nuclei by measurements at 25 Mc/sec.

**SYNTHESIS OF MODEL COMPOUNDS**

The compounds which have been prepared for use in these investigations, are listed in Table 1. Methods used for their synthesis are also indicated in the Table.

All the compounds, except for the dimethylaminohalogeno-phenylboranes, (VII) - (IX), were fully characterised by elemental analyses.

**PHYSICAL MEASUREMENTS**

Infrared spectra were recorded on a Perkin Elmer Model 21 (Sodium Chloride optics) and on a P.E. Model KL4 (potassium bromide optics). Samples were studied as pure materials. Compounds (I) - (VIII) were each characterised by having a strong absorption band in the range 1450 ± 100 cm\(^{-1}\), which may be attributed to the EN stretching frequency.\(^1\) Comparison of the spectra of the phosphorus compounds (XI) and (XII) with their boron analogues (I) and (II) confirms this assignment and moreover reveals that the FN stretching vibrations fall at 986 cm\(^{-1}\) for PhPClMe\(_2\) and at 971 cm\(^{-1}\) (asymmetric) and 957 cm\(^{-1}\) (symmetric) for PhP(NMe\(_2\))\(_2\).

Nuclear magnetic resonance spectra were recorded on a Varian Associates Model V4300B equipped with variable temperature probes or on an A.E.I. BS2 spectrometer. Spectra were recorded at 60, 40, and 25 Mc/sec.

Mathematical calculations were carried out on the Ferranti Mercury computer in the Department of Electrical Engineering, University of Manchester.

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RESULTS
Mathematical Approach to the Calculation of Barriers to Internal Rotation.

A quantitative treatment for the study of internal rotation in molecules by nuclear magnetic resonance has been developed, by suitable modification of the Bloch equations to take into account exchange between two equally abundant sites with equal transverse relaxation times. The most general treatment is that of McConnell, who has shown that the total r.f. magnetisation in such a system is given by

\[ G = \frac{i w M_0 \tau}{\tau^2} \left\{ 1 - \frac{1/\tau_2 - i (\Delta \omega_A + \Delta \omega_B)/2}{1/\tau_2 - i \Delta \omega_A} \right\} \]

where \( M_0 \) = total magnetisation
\( \tau_2 \) = Transverse Relaxation Time (assumed equal for the two environments)
\( \tau \) = Mean lifetimes of environments A and B
\( 1/\tau_2 = 1/\tau_A + 1/\tau_B \)
\( \Delta \omega_A = \Delta \omega_{0A} - w \)
\( w_{0A} \) = Larmor precession angular velocity of nuclei in environment A in the STATIC field only.
\( w \) = Angular velocity of the rotating magnetic field, \( H_1 \).
\( w_1 = \gamma H_1 \)
\( \gamma \) = Magnetogyric Ratio

If the internal chemical shift \( w_{0A} - w_{0B} = \delta w \), and the separation of the angular velocity, \( w \), from the mean shift \( w_{0A} - w_{0B} = w \),

Then:
\[ \Delta \omega_A + \Delta \omega_B = 2 \Delta \omega \]
\[ \Delta \omega_A - \Delta \omega_B = \delta w \]
\[ \Delta \omega_A = \Delta \omega + \delta w/2 \]
\[ \Delta \omega_B = \Delta \omega - \delta w/2 \].

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\[ G = \frac{i w_1 \frac{1}{2} \tau (2 + \frac{\tau}{T_2} - i \Delta w \tau)}{[1 + \tau(\frac{1}{T_2} - i \Delta w - i \delta \omega / 2)][1 + \tau(\frac{1}{T_2} - i \Delta w + i \delta \omega / 2)]} \]

An expression for the out of phase component of the r.f. magnetisation \( \mathbf{v} \), which is proportional to the intensity of absorption, can be obtained from the imaginary part of this expression for \( \mathbf{G} \).

\[ \mathbf{v} = \frac{w_1 \frac{1}{2} \tau (1 + \frac{\tau}{2T_2}) P + \frac{\tau}{2}(\Delta w)^2 (1 + \frac{\tau}{T_2})}{P^2 + (\Delta w)^2 (1 + \frac{\tau}{T_2})^2}. \]

\[ P = \frac{\tau}{2} [(\frac{1}{T_2} - \Delta w^2 + (\delta \omega / 2)^2) + \frac{1}{T_2}] \]

Differentiation of this expression to obtain extreme values of \( \mathbf{v} \), yields a fifth order equation in \( (\Delta w)^5 \)

\[ \frac{\tau^4}{T_2} (\Delta w)^5 + 8 \tau^2 s (1 + \frac{\tau}{T_2}) (\Delta w)^3 + 16 \left[\left(1 + \frac{\tau}{T_2}\right)^2 1 + \frac{\tau}{T_2}\right] \Delta w = 0 \]

The solutions to this equation are at \( \Delta w = 0 \), or

\[ \Delta w = \pm \left[ -23 \left(\frac{1 + \frac{\tau}{T_2}}{\tau}\right) \pm s^2 (\delta \omega) \middle(\frac{2T_2}{\tau^3} + 4\frac{T_2}{\tau^2} + 2 - \frac{1}{\tau}\right) \right]^{\frac{1}{2}} \]

The negative possibility in the second choice of signs may be disregarded since this will lead to complex roots.

If the second term of this expression is greater than the first, then the resultant two real roots will give an expression for the two maxima which will occur at positions \( \Delta w \) from a zero line and be given by

\[ \Delta w = \pm \left[ -23 \left(\frac{1 + \frac{\tau}{T_2}}{\tau}\right) + s^2 (\delta \omega) \middle(\frac{2T_2}{\tau^3} + 4\frac{T_2}{\tau^2} + 2 - \frac{1}{\tau}\right) \right]^{\frac{1}{2}} \]

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The observed separation of the two peaks $\delta w_{e} = 2|\Delta w|$,

$$\delta w_{e} = 2\left[-23\left(\frac{1}{\tau} + 2T_{2}\right) + \frac{3}{\tau}\left(\delta w\right)\left(\frac{2\tau}{\tau^{3}} + 4T_{2} + \frac{2}{\tau}\right)\right]^{\frac{1}{3}}$$

Hence $\frac{\delta w_{e}}{\delta w} = 2\left[-2\left(\frac{1}{T_{2}\delta w} + 2(T_{2}\delta w)^{2}\right) + \frac{3}{\delta w}\left(\frac{1}{\delta w} + 2T_{2}\delta w\right)\right]^{\frac{1}{3}}$

$$\left(\frac{1}{T_{2}\delta w} + \frac{\tau\delta w}{2(T_{2}\delta w)^{2}} + \frac{\delta w}{8}\right)^{\frac{1}{3}} \approx \left(\frac{2(T_{2}\delta w)^{2} + 4T_{2}\delta w + 2}{(\tau\delta w)^{3} + (\tau\delta w)^{2} + \tau\delta w}\right)^{\frac{1}{3}}$$

At zero exchange $\tau = \infty$ and $\delta w_{e}$, represented in this special case by $\delta w_{\infty}$ is given by

$$\frac{\delta w}{\delta w_{\infty}} = \left[\frac{1}{3} - \frac{4}{3(T_{2}\delta w_{\infty})^{2}} + \frac{2}{3}\left(1 + \frac{4}{(T_{2}\delta w_{\infty})^{2}} + \frac{16}{(T_{2}\delta w_{\infty})^{4}}\right)^{\frac{1}{3}} \right]^{\frac{1}{3}}$$

Using these expressions the variation of $\delta w_{e}/\delta w_{\infty}$ with $1/\tau \delta w$ for various values of $T_{2} \delta w$ have been computed. The results are shown graphically in diagram 2.

In addition to observations on peak maxima separation, 5,
information on reaction rates have been obtained from observations on

(i) The intensity ratio of central minimum/maxima

(ii) The bandwidth at half height after coalescence.

Using the information briefly outlined above, equations have been derived which allow use to be made of these parameters. The resultant expressions are

\[
\text{(i) Minimum intensity} = \frac{(1 + \frac{\tau \Delta w}{2T_2 \delta w})}{\text{Maximum intensity}} \left( \frac{3}{\delta w} \right)^2 \left( \frac{1 + \frac{\tau \Delta w}{2T_2 \delta w}}{\frac{\tau \Delta w}{\delta w}} \right) + \frac{\frac{1}{4} \left( \frac{5}{\delta w} \right)^2 \left( 1 + \frac{\tau \Delta w}{T_2 \delta w} \right)^2}{\left( \frac{\delta w}{\delta w} \right)^2 \left( 1 + \frac{\tau \Delta w}{T_2 \delta w} \right)} \]

\[
\frac{P}{\delta w} = \frac{\tau \Delta w}{2} \left[ \frac{1}{(T_2 \delta w)^2} - \frac{1}{4} \left( \frac{\delta w}{\delta w} \right)^2 + \frac{1}{8} \right] + \frac{1}{T_2 \delta w} \]

\[
S = \frac{1}{T_2 \delta w} + \frac{\tau \delta w}{2(T_2 \delta w)^2} + \frac{\tau \delta w}{8} \]

\[
\frac{\delta w}{\delta w} = 2 \left\{ \frac{4(3/\delta w)}{\tau \delta w} \frac{\tau \delta w}{\tau \delta w} + \frac{T_2 \delta w}{2T_2 \delta w} - \frac{2}{(\tau \delta w)^2} \left( \frac{1 + \tau \delta w}{T_2 \delta w} \right)^2 + 2 \left[ \frac{1}{(\tau \delta w)^2} + \frac{\tau \delta w}{T_2 \delta w} \right] - \frac{4(3/\delta w)}{(\tau \delta w)^2} \frac{\tau \delta w}{\tau \delta w} + \frac{T_2 \delta w}{2T_2 \delta w} \left( \frac{1 + \tau \delta w}{T_2 \delta w} \right)^2 \right\} + \frac{4 \left( \frac{3}{\delta w} \right)^2 \left( \frac{\tau \delta w}{\tau \delta w} + \frac{T_2 \delta w}{T_2 \delta w} \right)^2 + \left( \frac{3}{\delta w} \right)^2 \left( \frac{\tau \delta w}{\tau \delta w} + \frac{T_2 \delta w}{T_2 \delta w} \right)^2}{(\tau \delta w)^2} \}
\]

Both these expressions only contain terms in $T_2 \delta w$ and

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CONTRAIRS

DIAGRAM 3

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$\frac{1}{\sigma} \frac{\delta w}{\delta w}$ and therefore the variation of the appropriate parameter (min./max. or $\frac{\delta w}{\delta w}$) with $\frac{1}{\sigma} \frac{\delta w}{\delta w}$ for various values of $T_2$ $\delta w$ can be computed. The results of such calculations are shown in diagrams 3 and 4.

It is well known that the reaction rate constant ($k$) for a first order reaction $= \frac{1}{\sigma} \frac{k}{\delta w}$.

Observations upon:
(i) Separation of peak maxima
(ii) Minimum/maximum ratio
(iii) Band width at half height after coalescence will allow values of $k$ to be calculated from experimental observations at various temperatures. If the Arrhenius expression, $k = Ae^{-Ea/kT}$, is assumed to apply then $Ea$, the energy of activation for the reaction, can be calculated.

In practice the graphical results reproduced in diagrams 2, 3 and 4 are used as master graphs from which values of $k/\delta w$ can be read for each experimental observation.

<table>
<thead>
<tr>
<th>Calculated from observations on</th>
<th>Energy Barrier to Rotation (k.cals) based upon</th>
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<tr>
<td></td>
<td>$T_2 \delta w_a = 10$ Radians</td>
</tr>
<tr>
<td>Band Maxima SepH</td>
<td>14.5</td>
</tr>
<tr>
<td>Minimum Maximum Intensity Ratio</td>
<td>18.1</td>
</tr>
<tr>
<td>Band Width at Half Height</td>
<td>19.5</td>
</tr>
<tr>
<td>Transition State Theory</td>
<td>($\Delta G$) = 20.7</td>
</tr>
</tbody>
</table>

**TABLE 2.** Showing values of $Ea$ for C$_6$H$_5$KCl·Me$_2$, at three values of $T_2$ $\delta w_a$ calculated from various experimental observations. Experimental value of $T_2 \delta w_a = 9.6$ Radians

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A value for the energy barrier to rotation can also be calculated from the temperature at which the doublet collapses to a single peak and the value of the k at this temperature by substitution in the transition state expression \( k = \frac{m}{5^s} e^{-\Delta H/kT} \).

Values of the energy barrier to rotation about the BN bond in phenylidimethylaminochloroborane, calculated from the experimental observations discussed above, are given in Table 2. Values of \( 2\delta_1 \) for three values of \( I \delta_0 (5, 10 \text{ and } \pi \text{ radians}) \) have been calculated, for each kind of experimental observation. The closest agreement occurs when \( I \delta_0 = 10 \), and this value is the nearest of the three to the value obtained experimentally (9.6 radians).

BIBLIOGRAPHY

   (b) Hill, Gerrard, Lappert, Mountfield, and Pyszora, J.Chem.