The Status of Laser Separation of Boron Isotopes - June 1974

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ABSTRACT

A 14% enrichment in the ratio of $^{10}\text{B}/^{11}\text{B}$ has been achieved by selective excitation by $^{11}\text{BCl}_3$ ($v_3$) with a CO$_2$ laser followed by preferential photodissociation of the excited state molecules. The subsequent photochemistry used O$_2$ as a scavenger.

I. INTRODUCTION

At this time we can report a 14% isotopic enrichment of a 50-ug sample of BCl$_3$ obtained with 3 pulses of laser radiation using two photon induced photochemistry. This mass of material represents a relatively large sample in comparison to other recent work in the field and, furthermore, the present results indicate that both the enrichment and the yield can be greatly improved by the development of a brighter UV source.

As stated we have employed selective two photon dissociation of BCl$_3$ in the presence of chemical scavengers. The first step is the selective excitation of $^{11}\text{BCl}_3$ in the $v_3$ mode using the P(20) line of a CO$_2$ laser. This is immediately followed by photodissociation of the excited state molecules yielding fragments containing an enhanced fraction of $^{11}\text{B}/^{10}\text{B}$. The fragments of the photodissociation are then consumed by a chemical scavenger. In the present case O$_2$ has been used as the principal scavenger leading to a product which has a much lower vapor pressure than the BCl$_3$. Physical separation of the two isotopes is thus accomplished by trapping of the product gas onto a cold surface while leaving the $^{10}\text{B}$ enriched BCl$_3$ in the gas phase. Subsequent portions of this report will examine in some detail the necessary physical properties of BCl$_3$ which allow the present process to work and conclude by presenting the isotopic enrichment obtained to date along with projected future experiments.

II. INFRARED REQUIREMENTS

Fig. 1. IR absorption spectrum of BCl$_3$ to the $v_3$ mode showing the isotope shift between $^{10}\text{BCl}_3$ and $^{11}\text{BCl}_3$. Path length was 10.2 cm. Pressure was not measured precisely.
Figure 1 displays the absorption spectrum of 
BCl$_3$ in the vicinity of 1000 cm$^{-1}$ along with the 
location of many CO$_2$ laser lines as presented in Refs 
(2-4). The attenuation coefficients and saturation 
flux for many of these lines are given in Ref. 3. 
From these data it is readily observed that quanti-
ties of BCl$_3$ on the order of 10 - 100 torr can be 
promoted to the $v_3$ mode using CO$_2$ laser powers 
readily obtainable with today's technology.  
The relaxation of the $v_3$ mode by vibration-vi-
bration (V-V) transfer is known to be rapid and the 
equilibration of excitation energy between $^{13}$BCl$_3$ 
($v_3$) and $^{10}$BCl$_3$ ($v_3$) proceeds with a rate of 

$$\frac{1}{\tau} = 2 \times 10^6 \text{ sec}^{-1} \text{ torr}^{-1}.$$  

(1) 
To avoid scrambling of the selected isotopic state 
the vibrationally excited $^{13}$BCl$_3$ must be dissociated 
on a time scale short compare to this V-V transfer 
rate. This rapid dissociation rate requires in turn 
a large uv photon flux as discussed in the following 
section.  
III. ULTRAVIOLET REQUIREMENTS  
Figure 2 displays the measured uv absorption 
of BCl$_3$ containing a natural abundance of both B and 
Cl isotopes. The absorption spectrum was measured 
on a Cary Model 14 spectrophotometer with a 10-cm 
quartz absorption cell at room temperature. A 
hydrogen lamp was used for the light source. A BCl$_3$ 
pressure equal to its vapor pressure at the temper-
ature of solid CO$_2$ was used to record spectrum A of 
Fig. 2. This pressure is approximately 4.0 torr. 
Spectrum B was run at a pressure of 2.1 torr. 
The peak at 207.6 nm was recorded at 0.05 nm/s. 
At 210 nm the dispersion of the Cary is 0.29 
mm when using a slit of 0.22 mm. No evidence of 
structure is observed in the 207.6-nm peak at either 
pressure. Since matched sample cells were not avail-
able it is necessary to subtract the background 
spectrum C of sample cell with vacuum from the re-
sults A and B. To obtain greater precision in the 
measurement of the extinction coefficient of BCl$_3$ 
in the ultraviolet, a slidewire was used which ex-
pected the optical density scale tenfold. An 
optical density of 0.046 was recorded with this 

\begin{figure}[h] 
\centering 
\includegraphics[width=0.8\textwidth]{fig2.png} 
\caption{uv absorption of BCl$_3$ near 207.6 nm param-
metric in pressure.} 
\end{figure} 

slidewire with 4 torr of BCl$_3$ in a 10-cm cell. 
Defining the extinction coefficient of BCl$_3$ by the 
expression: \(I/I_0 = \exp (-\varepsilon p)\), where \(\varepsilon\) is the 
extinction coefficient of BCl$_3$, \(p\) is the pressure in 
\text{torr}, and \(x\) is the path length in \text{cm}, a value of 
0.003 cm$^{-1}$ torr$^{-1}$ is computed for \(\varepsilon\) at room 
temperature. 
Using the measured width of the 207.6-nm ab-
sorption and a Morse potential ground state with 
constants appropriate to the $v_3$ mode one can con-
struct the potential curves shown in Fig. 3 using 
the theory of Winans and Stueckelberg.\textsuperscript{5} The cal-
culated slope of the upper state of the 207.6-nm 
transition is -1.6 ev/A. 
Using the measured absorption curve shown in 
Fig. 2 and assuming that all the energy of the 
$v_3$ mode is available for dissociation one can con-
struct the excited state absorption curve displayed 
in Fig. 4. This curve does not account for pos-
sible Frank-Condon shifts of the dissociation 
energy indicated in Fig.3. From these data we 
conclude that uv radiation in the wavelength range 
213.0 $\leq \lambda \leq$ 215.0 nm is desirable to obtain at 
least a 10:1 enhancement in absorption from the 
excited state over absorption in the wings of the 
ground state.
From the measured uv absorption coefficient and the known V-V relaxation time, Eq. (1), one can compute the required uv flux for efficient enrichment as

$$\phi = \frac{\frac{\text{RN}}{R}}{a^2} \times 6 \text{ ev} = 1.9 \times 10^7 \text{ W/cm}^2/\text{torr BCl}_3$$

where $a = 1.0 \times 10^{-19} \text{ cm}^2$ is the uv absorption cross section, $R = 5.7 \times 10^{-11} \text{ cm}^3/\text{s}$ is the V-V transfer rate from Eq. (1) and $N$ is the BCl$_3$ number density. Flux densities of this magnitude in the desired 2.0-nm bandwidth almost certainly require a uv laser. However, no lasers at the appropriate wavelength are currently available and development of these sources must receive attention in the immediate future.

IV. PHOTOCHEMISTRY

To assess the results of absorption of uv light by BCl$_3$ in the absence of other gases a sample cell containing 4.0 torr of pure BCl$_3$ was placed in front of a 1-kW deuterium discharge lamp for 1 h. No evidence of solid formation or alteration in the uv or ir absorption spectra of the gas was observed.

Fig. 3. Morse potential curve for the $v_3$ mode of BCl$_3$ plus estimated excited state from uv absorption. Indicated wavelengths are for transitions from the probability maxima regions of the ground and first excited states.

Fig. 4. Smooth curve fit to uv absorption from ground state at p=4 torr plus absorption from the first vibrational level of the $v_3$ mode assuming conservation of energy. The relative amplitudes assume 50% of the $^{14}$BCl$_3$ has been promoted to $v=1$ of the $v_3$ mode.
However there was evidence that a radical species had been formed because of a markedly improved transmission of the empty sample cell. The radical species was most likely Cl which rapidly recombined with BC\textsubscript{12} to reinstate the BC\textsubscript{13} population.

A second photolysis experiment was then performed to examine the scavenging action of an olefin for the radiation fragments of BC\textsubscript{13}. The system consisted of 23 torr of research grade (Phillips Petroleum, 99.7 mol\% purity) ethylene and 40 torr of BC\textsubscript{13} in a 10-cm quartz cell. There was no apparent reaction at room temperature in the absence of radiation. A mass spectrographic analysis of the product formed after 2 h of radiation with the continuum from a 1-kW deuterium lamp indicated that approximately 12\% of the product was ethyl chloride. The kinetic aspects of the effective addition of HCl to C\textsubscript{2}H\textsubscript{4} were not examined further. Unreacted BC\textsubscript{13} and C\textsubscript{2}H\textsubscript{4} were also present.

From the results of these experiments it was clear that absorption of uv light by BC\textsubscript{13} could be used to initiate photochemical reactions and it appeared feasible to separate boron isotopes by the process described in the introduction if the appropriate scavenger could be selected. The scavenger must be nonreactive with BC\textsubscript{13} at moderate pressures, exhibit no uv or ir absorption at the wavelengths of interest, and produce a simple chemistry with little or no scrambling of isotopic information.

A summary of the scavengers which have been studied to date is given in Table I. All of the present experimental attempts to achieve isotopic enrichment have used O\textsubscript{2} as a scavenger and will be described in the following sections. This does not imply that O\textsubscript{2} is the best scavenger but of the present list it was the most convenient experimentally.

V. EXPERIMENTAL APPARATUS

It was noted in Section II that the uv requirements demand light of laser intensities at frequencies at which lasers are not currently available. As an alternative we have used BC\textsubscript{13} to filter a Xe flash lamp in the configuration displayed in Fig. 5.

The reaction chamber shown in Fig. 5a is constructed of quartz with KCl windows mounted at 45° on either end. The CO\textsubscript{2} laser pulse is provided by a 1-m helical pin laser and is propagated axially through the 3-mm capillary tube. The CO\textsubscript{2} laser provides 150 mJ on the P(20) line with a temporal FWHM of 1.5 \mu s as measured with a Au-Ge detector into a 50-Ω load. The 3-mm capillary is centered at the intensity maximum of the unfocused CO\textsubscript{2} laser beam and a nominal energy of 11 mJ is transmitted through the evacuated capillary tube. Burn patterns indicate that this energy is uniformly distributed across the 3-mm diameter of the capillary tube. The peak CO\textsubscript{2} power as determined from oscilloscope tracings and the known geometry was about 10\textsuperscript{5} W/cm\textsuperscript{2}.

<table>
<thead>
<tr>
<th>Scavenger</th>
<th>Light Source</th>
<th>Product</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>C\textsubscript{2}H\textsubscript{4}</td>
<td>CO D\textsubscript{2} lamp, and 206.1-\textmu m line of CO I\textsubscript{2} lamp</td>
<td>C\textsubscript{2}H\textsubscript{4}Cl</td>
<td>Ethylene absorbs 10.6 \mu m light</td>
</tr>
<tr>
<td>C\textsubscript{2}H\textsubscript{2}</td>
<td>-</td>
<td>-</td>
<td>Reacts spontaneously with BC\textsubscript{13} at 40 torr pressure</td>
</tr>
<tr>
<td>cis-butene-2</td>
<td>uv lamps also CO\textsubscript{2} laser only</td>
<td>Dark brown, sticky liquid</td>
<td>Note that CO\textsubscript{2} laser alone produces a reaction</td>
</tr>
<tr>
<td>O\textsubscript{2}</td>
<td>D\textsubscript{2}, I\textsubscript{2}, CO\textsubscript{2}, and Xe flash lamp</td>
<td>(BOCl)\textsubscript{3} plus white solid</td>
<td>Product is only tentatively identified based upon work of Refs. 6,7. See present ir spectrum in Fig. 7. CO\textsubscript{2} laser alone would not induce a reaction.</td>
</tr>
</tbody>
</table>
Fig. 5. Experimental configuration of the photolysis chamber.

The reaction chamber is surrounded by a coaxial jacket of quartz containing pure BCl₃ at pressures of 600-700 torr. This acts as a filter for radiation providing a contrast ratio of about 10:1 between 215.0 nm and 207.6 nm light as shown in Fig. 6a.

Since pure BCl₃ did not suffer photodecomposition as noted in Section III the filter showed very little aging on a span of 20 to 30 shots. The entire reaction chamber is placed at one focus of a Raytheon model LH5 ruby laser flash lamp cavity. A Xe, FX-5, flash lamp is placed at the other focus and discharges 840 J of electrical energy in 250 µs with the pulse shape shown by the lower trace of Fig. 6b. The CO₂ laser was triggered at the peak of the uv pulse as shown in Fig. 6b.

The output spectrum of the Xe lamp was not measured; thus it is difficult to state accurately the energy contained in the desired uv bandwidth. However it was noted that this lamp was very efficient in initiating the photochemical reaction between BCl₃ and O₂. Six torr of BCl₃ in an excess of O₂ could be completely reacted using 15 shots of the uv lamp alone when no filter gas was employed. From the known BCl₃ pressure and volume one can then infer a uv output of ~0.1 J/shot in the bandwidth of the 207.6-nm absorption feature. This assumes no chain reactions were occurring which is consistent with

Fig. 6. (a) Spectral response of uv filter. The cutoff below 205 nm is due to the quartz glass.
(b) Oscilloscope tracing showing timing of uv and ir radiation pulses. Sweep speed is 50 µs/div,
the fact that the irradiation could be stopped after a smaller number of uv shots and the remaining (BCl$_3$, O$_2$) mixture would show no further reaction for time scales on the order of at least 24 h.

VI. RESULTS AND FUTURE WORK

The first experiments with the flash lamp system were designed to verify the (BCl$_3$, O$_2$) photochemistry described in Ref. 6. Figure 7 displays the ir spectrum of the residual gas resulting from the irradiation of 3 torr BCl$_3$ and 6 torr O$_2$ by three flashes of the unfiltered Xe lamp. Three distinguishable species are present in this sample: the BCl$_3$, a solid product which is deposited on the windows, and a gaseous product showing peaks attributed in Ref. 6 to (BOCl)$_3$. In addition to the peaks observed in Ref. 6 we observe 4 additional absorption peaks lying between 800 cm$^{-1}$ and 950 cm$^{-1}$ which are attributed to the same species giving rise to the strong 1370 cm$^{-1}$ absorption feature.

![Fig. 7. ir absorption spectrum of residual gas following irradiation of 3 torr of BCl$_3$ and 6 torr of O$_2$ by three flashes from the unfiltered Xe lamp. Absorption features, except as noted, are assigned to (BOCl)$_3$.](image)

The peaks identified with the gas phase product in the present work are compared with those of Ref. 6 in Table II. Some of the new absorption features can be assigned to modes of (BOCl)$_3$ (g) using the spectrum of (BOCl)$_3$ (s) given in Ref. 7 however, we have not yet attempted a detailed classification of the product and its spectrum.

Attempts were made to determine the identity of the product by analysis in a Bendix MA3-A time-of-flight mass spectrometer. Mass peaks which were not observed in scans of pure BCl$_3$ could be attributed to BO$^+$, BO$_2$Cl$^+$, BOCl$_2^+$, and BO$_2$Cl$_2^+$. However, from these results we could not identify a parent molecule. For the remainder of this report we will identify the gaseous product as (BOCl)$_3$ on the basis of its ir spectrum however this identification is tentative and subject to further investigation.

In Ref. 6 it was stated that the gaseous (BOCl)$_3$ was unstable with respect to decomposition into the solid phase product. We found this to be the case only in sample cells which had recently been exposed to room air. The ir sample cells used in this investigation were made of brass and used KCl windows. Once the solid phase product was present, as demonstrated by its ir absorption feature, the (BOCl)$_3$ could be contained for periods of several days at room temperature without evidence of further decomposition. These facts suggest that the "instability" of (BOCl)$_3$ is principally a manifestation of a very rapid reaction rate with H$_2$O adsorbed onto

<table>
<thead>
<tr>
<th>Absorption peak (present work)</th>
<th>Ref. 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>790 cm$^{-1}$</td>
<td>620</td>
</tr>
<tr>
<td>810</td>
<td></td>
</tr>
<tr>
<td>835 (shoulder at 845)</td>
<td></td>
</tr>
<tr>
<td>880 (structure)</td>
<td></td>
</tr>
<tr>
<td>930</td>
<td></td>
</tr>
<tr>
<td>1210</td>
<td>1210</td>
</tr>
<tr>
<td>1370</td>
<td>1385</td>
</tr>
<tr>
<td>1405</td>
<td>1430</td>
</tr>
<tr>
<td>1450-1600 (much structure)</td>
<td>1470</td>
</tr>
</tbody>
</table>
were made to monitor the ir fluorescence of the BC13. No attempt was made to measure the ir fluorescence of the BCI3. No reaction between BCI3 and 02 could be induced by the CO2 laser alone at the power densities employed in this investigation. Also, in contrast to the work of Karlov 2 where much higher power CO2 laser pulses were used, we observed no visible fluorescence from the irradiated BCI3. No attempts were made to monitor the ir fluorescence of the BCI3 gas.

We had initially intended to measure isotopic enrichment by changes in the ratio of the area of the ir absorption of 10BC13 (v3) to 11BC13 (v3). However, the discovery of the (BOC1)3 feature at 930 cm-1 complicated this measurement by adding an underlying background to the 113C13 (v3) mode at 947 cm-1. For this reason all isotopic analyses of the irradiated gases were performed with the Bendix time-of-flight mass spectrometer.

Table III presents the results of mass spectral analyses of 10 separate samples of pure BCI3 as supplied by Matheson Co. A CRS-160 Infotronics digital read out and a MDS P-20 printer was used for data acquisition. The results of these analyses were used to establish the cracking pattern of BCI3 in our mass spectrometer and also to establish a baseline for the ratio of 10B/11B in the gas received from Matheson. The dominant ion in the fragmentation of BCI3 is BCI2+. For the two 35Cl isotopes the boron peaks occur at masses 80 and 81. We found the ratio of mass 80 to 81 in our sample of BCI3 to be .253 ± .002 and free from interference with mass peaks of the product. The ratio of mass 80 to 81 was thus used for all subsequent analysis of the boron 10 to 11 ratio in BCI3.

* Indicated numbers for F containing species are typical but actual values varied with history of the mass spectrometer.

Table III cont.

<table>
<thead>
<tr>
<th>Mass</th>
<th>Species</th>
<th>Relative Intensity</th>
<th>Experimental Isotopic Ratio</th>
<th>Theoretical Isotopic Ratio Based on Natural Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.0</td>
<td>10Cl+</td>
<td>.019</td>
<td>.253 ± .002</td>
<td>.247</td>
</tr>
<tr>
<td>11.0</td>
<td>11Cl+</td>
<td>.077</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>17.5</td>
<td>35Cl4+</td>
<td>.003</td>
<td>-</td>
<td>1.000</td>
</tr>
<tr>
<td>18.0</td>
<td>35Cl2+</td>
<td>.036</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>18.5</td>
<td>37Cl2+</td>
<td>.036</td>
<td>1.000</td>
<td>1.000</td>
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<tr>
<td>19.0</td>
<td>35Cl+</td>
<td>.012 (6)</td>
<td>.326 ± .003</td>
<td>.247</td>
</tr>
<tr>
<td>20.0</td>
<td>11Cl+</td>
<td>.036</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>25.0</td>
<td>35Cl+</td>
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<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>26.0</td>
<td>35Cl2</td>
<td>.181</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>27.0</td>
<td>37Cl+</td>
<td>.067</td>
<td>.316 ± .010</td>
<td>.247</td>
</tr>
<tr>
<td>28.0</td>
<td>35Cl2+</td>
<td>.032</td>
<td>.289 ± .012</td>
<td>.247</td>
</tr>
<tr>
<td>30.0</td>
<td>10Cl3+ 35Cl+</td>
<td>.010</td>
<td>-</td>
<td>.247</td>
</tr>
<tr>
<td>31.0</td>
<td>11Cl3+ 35Cl+</td>
<td>.036</td>
<td>-</td>
<td>1.000</td>
</tr>
<tr>
<td>32.0</td>
<td>10Cl3+ 37Cl+</td>
<td>.003</td>
<td>-</td>
<td>.247</td>
</tr>
<tr>
<td>33.0</td>
<td>11Cl3+ 37Cl+</td>
<td>.010</td>
<td>-</td>
<td>.247</td>
</tr>
<tr>
<td>34.0</td>
<td>10Cl3+ 39Cl+</td>
<td>.006 (5)</td>
<td>-</td>
<td>.247</td>
</tr>
<tr>
<td>35.0</td>
<td>11Cl3+ 39Cl+</td>
<td>.006 (5)</td>
<td>-</td>
<td>.247</td>
</tr>
<tr>
<td>36.0</td>
<td>10Cl3+ 40Cl+</td>
<td>.075</td>
<td>-</td>
<td>.247</td>
</tr>
<tr>
<td>37.0</td>
<td>11Cl3+ 40Cl+</td>
<td>.075</td>
<td>-</td>
<td>.247</td>
</tr>
</tbody>
</table>

* Varied depending on history of the mass spectrometer. Hydrogen compounds appear to come from a reaction between BCI3 and H20 adsorbed in the mass spectrometer vacuum lines.

+ Varied depending on history of the mass spectrometer. The primary source of F was the mass spectrometer which had been used previously to examine fluorine compounds.
The ir spectrum of residual gas following irradiation of 4 torr BCl₃ plus 16 torr O₂ by 10 shots of filtered uv radiation. The ir spectrum of residual gas following irradiation of (BCl₃, O₂) mixture as in (a) by 10 shots of filtered uv plus ir laser radiation.

Figure 8 compares the ir spectrum of the residual gas following irradiation of 6 torr of BCl₃ in 12 torr of O₂ by 10 shots using in (a), filtered uv light only and, (b) filtered uv light plus ir radiation. The filter consisted of 600 torr of pure BCl₃ in the coaxial jacket as described above. Notice that there appears to have been some leakage of light through the filter because some (BCCl)₃ product is formed. However, the greater effectiveness of the filtered uv-ir combination in inducing the photochemical reaction is clearly demonstrated by the destruction of all the BCl₃ in case b. This result is a necessary condition for isotope separation since only the ir photons are isotopically selective.

For the results shown in Fig. 8b both isotopic species were reacted because the ir laser pulse was triggered 200 μs before the peak of the uv pulse. Since the BCl₃ pressure was 6 torr the timing delay allowed complete V-V equilibration of the ir energy between both isotopes during the duration of the uv pulse and no isotopic selective could be expected.

At this point conditions were defined for a series of experiments to attempt to show isotopic enrichment. All of the experiments used 5 shots of the filtered uv plus ir laser combination with the timing shown in Fig. 6. The filter was 600 torr of BCl₃ in all cases. The oxygen pressure was maintained at 20 torr and the BCl₃ pressure varied. The ratio of mass 80 to 81 was used as the principal diagnostic for the ¹⁰B to ¹¹B ratio.

Figure 9 displays the results of this analysis as a function of the original BCl₃ pressure in the reaction chamber. The error bars on the data points are pessimistic in that they display the full range of values for the ratio of 80:81 obtained in from 3 to 10 scans of the sample by the mass spectrometer. The enrichment of the residual gas in ¹⁰B increases to a value of 14% at an initial BCl₃ pressure of 0.8 torr which is consistent with a uv flux limited process as indicated by the dashed lines. This model will be discussed below.

![Graph showing the ratio of ¹⁰B/¹¹B as determined by mass spectrum analyses of residual gas following irradiation by 5 flashes of filtered uv plus ir laser radiation as a function of initial BCl₃ pressure. Error bars display the full range of observed data. Dashed lines indicate expected results based upon rapid V-V transfer between ¹¹BCl₃ (ν₁) and ¹⁰BCl₃ (ν₂). Note 1 kPa = 7.502 torr.](attachment:image.png)
The data indicated by the open circles and triangles represent null experiments where all steps were repeated just as before with the exception of triggering the CO$_2$ laser. These null experiments give a $^{10}\text{B}/^{11}\text{B}$ ratio in good agreement with the value of 0.253 obtained previously in analysis of pure BCI$_3$. Also from the null experiments no pressure dependence is observed in the measured $^{10}\text{B}/^{11}\text{B}$ ratio which tends to rule out the possibility of a systematic error in the mass spectrometer yielding an apparent enrichment with decreasing BCI$_3$ partial pressure.

For weak irradiation the time rate of change of the concentrations of $^{10}\text{B}$(v$_3$) $\equiv$ X$_{10}$, $^{11}\text{B}$(v$_3$) $\equiv$ X$_{11}$ and the products may be described by the following equations:

$$\frac{d}{dt} X_{11} = \sigma_{ir} \phi_{ir} N - (R N + \alpha_{uv} \phi_{uv}) X_{11} \tag{3}$$

$$\frac{d}{dt} X_{10} = R N X_{11} - \alpha_{uv} \phi_{uv} X_{10} \tag{4}$$

$$\frac{d}{dt} P_{11} = \sigma_{uv} \phi_{uv} X_{11} \tag{5}$$

$$\frac{d}{dt} P_{10} = \sigma_{uv} \phi_{uv} X_{10} \tag{6}$$

where N is the BCI$_3$ concentration and is assumed to be constant, P$_{10}$ and P$_{11}$ are the photodissociation fragments of $^{10}\text{B}$(v$_3$) and $^{11}\text{B}$(v$_3$), respectively, R is the V-V transfer rate used in Eq. (2), $\sigma_{ir}$ and $\sigma_{uv}$ are the ir and uv absorption cross sections and $\phi_{ir}$ and $\phi_{uv}$ are the ir and uv photon fluxes. With the assumptions that N, $\phi_{ir}$, and $\phi_{uv}$ are independent of time Eqs. (3-6) are readily integrated. From the resulting solutions and consistent with assumptions of Eqs. (3-6) that the product produced is small compared with the initial BCI$_3$ concentration one obtains for the ratio of $^{10}\text{B}/^{11}\text{B}$ in the residual gas:

$$\left(\frac{^{10}\text{B}}{^{11}\text{B}}\right)_{\text{residual}} = \left(\frac{^{10}\text{B}}{^{11}\text{B}}\right)_{\text{initial}} \times \left[ 1 + \frac{t_p}{t_{\text{two}}} \right] \left(\frac{\alpha_{uv} \phi_{uv}}{R N} \right) \left(\frac{\sigma_{ir} \phi_{ir}}{t_p} \right)$$

where $t_p \gg (R N + \sigma_{uv} \phi_{uv})^{-1}$ is the duration of the radiation pulse. Evaluating Eq. (7) with parameters $\sigma_{uv} = 1 \times 10^{-19}$ cm$^2$, $R = 5.7 \times 10^{-11}$ cm$^3$/s, $N$(cm$^{-3}$) = 3.52x10$^{16}$ BCI$_3$ (torr), and $\sigma_{ir} \phi_{ir} t_p = 20$ gives the results parametric in $\phi_{uv}$ indicated by the dashed lines in Fig. 9.

These simple analytic results appear to be in good agreement with the experimental data when values for the uv flux appropriate to experimental conditions are assumed. One thus infers that the present experiment was severely deficient in uv power and considerable scrambling of ir excitation was induced by V-V transfer. The most immediate modification of the experimental apparatus will be the construction of a faster flash lamp to provide a higher peak power. Preliminary results also indicate that a D$_2$ filled lamp will provide more radiation in the desired bandwidth. On a longer time scale we will attempt to obtain laser radiation at the required wavelength using harmonic generation in ADP crystals as described by Massey.

Other experiments currently in progress involve attempts to obtain isotopic enrichment by CO$_2$ laser induced chemistry between BCI$_3$ and numerous olefins. Should these experiments prove successful it would be possible to eliminate the need to develop a hard uv source. However, one step laser induced chemistry is severely limited in its approach to isotope separation since it requires the reaction time to be short compared to the V-V exchange time while at the same time keeping the V-T deactivation of the selected state by the reagent long compared to the chemical reaction time. It may prove very difficult to find a reagent which will meet all these requirements.

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REFERENCES
1. See, proceedings of VIII Int. Quantum Elect. Conf. session Q, to be published in IEEE-J. Q.E.