Atomic and molecular spectra as probes for fundamental constants

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There are three fundamental constants, which influence atomic and molecular spectra:

- Fine structure constant $\alpha = \frac{e^2}{\hbar c}$;
- Electron to proton mass ratio $\beta = \frac{m_e}{m_p}$;
- Nuclear gyromagnetic ratio $g_n$. 

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When we are studying variation of fundamental constants, we are looking for lines with high sensitivity to the variation of fundamental constants. The dimensionless sensitivity coefficients are defined as:

$$\frac{\delta \omega}{\omega} = K_\alpha \frac{\delta \alpha}{\alpha} + K_\beta \frac{\delta \beta}{\beta} + K_g \frac{\delta g_n}{g_n}.$$ 

In astrophysics such frequency shifts lead to the difference between the apparent and actual redshifts $z'$ and $z$:

$$\frac{\delta \omega}{\omega} = - \frac{z' - z}{1 + z'}$$

When we observe two lines with different sensitivities, their apparent redshifts will differ if fundamental constants has changed during the time passed:

$$\frac{\delta z'}{1 + z'} = - \Delta K_\alpha \frac{\delta \alpha}{\alpha} - \Delta K_\beta \frac{\delta \beta}{\beta} - \Delta K_g \frac{\delta g_n}{g_n}.$$
Sensitivity coefficients for different wavebands

<table>
<thead>
<tr>
<th>Transition</th>
<th>( K_\alpha )</th>
<th>( K_\beta )</th>
<th>( K_g )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Optical and UV bands</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>typical E1-transition in atoms</td>
<td>( 10^{-2} – 10^{-1} )</td>
<td>( 10^{-3} )</td>
<td>( 10^{-7} )</td>
</tr>
<tr>
<td>electronic transitions in molecules</td>
<td>( 10^{-2} )</td>
<td>( 10^{-2} )</td>
<td>( 10^{-7} )</td>
</tr>
<tr>
<td><strong>Microwave and FIR bands</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fine-structure M1-transitions</td>
<td>2</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>vibrational transitions</td>
<td>0.0</td>
<td>0.5</td>
<td>0.0</td>
</tr>
<tr>
<td>rotational transitions</td>
<td>0.0</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>21-cm hyperfine transition in hydrogen</td>
<td>2.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>18-cm ( \Lambda )-doublet line in OH</td>
<td>( -1.14 )</td>
<td>2.55</td>
<td>0.0</td>
</tr>
<tr>
<td>1.25-cm inversion line in ( \text{NH}_3 )</td>
<td>0.0</td>
<td>4.5</td>
<td>0.0</td>
</tr>
</tbody>
</table>
One of the best studied extragalactic microwave spectra belongs to the object \( B0218+357 \) at \( z = 0.68 \) (look-back time of approximately 6.3 Gyr). This spectrum includes 21-cm Hydrogen line, several rotational lines of OH, HCO\(^{+}\), and HCN molecules, 18-cm \( \Lambda \)-doublet lines of OH molecule, and several inversion lines of NH\(_3\). These lines were used to place limits on variations of all three fundamental constants:

\[
\begin{align*}
\delta \beta / \beta &= (-0.6 \pm 1.9) \times 10^{-6}, \\
\delta \alpha / \alpha &= (0.9 \pm 6.4) \times 10^{-6}, \\
\delta g_n / g_n &= (0 \pm 17) \times 10^{-6}.
\end{align*}
\]
Lambda-doublet transitions (spin decoupling)

OH molecule
\( \Delta F=0 \) lines

- \( K_\alpha \) for \( \Pi_{1/2} \)
- \( K_\alpha \) for \( \Pi_{3/2} \)
- \( K_\beta \) for \( \Pi_{1/2} \)
- \( K_\beta \) for \( \Pi_{3/2} \)
Λ-doublet transitions (spin decoupling)

CH molecule
ΔF=0 lines

- Kα for Π₁/₂
- Kα for Π₃/₂
- Kβ for Π₁/₂
- Kβ for Π₃/₂

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Lambda-doublet transitions (hyperfine anomaly)

15NO molecule
state Π_{3/2}

Kα for ΔF=0
Kα for ΔF=−1
Kα for ΔF=1
Kβ for ΔF=0
Kβ for ΔF=−1
Kβ for ΔF=1

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