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Zeeman spectroscopy of CaH molecules in a magnetic trap

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(Received 28 September 1998; accepted 27 October 1998)

In a recent experiment [Weinstein et al., Nature 395, 148 (1998)] we magnetically trapped $10^8$ ground-state calcium monohydride molecules, CaH($X^2\Sigma,v''=0,J''=0$). The molecules were prepared by laser ablation of a solid sample of CaH$_2$ and loaded via thermalization with a cold ($<1$ K) $^3$He buffer gas. The magnetic trap was formed by superconducting coils arranged in the anti-Helmholtz configuration. The detection was done by laser fluorescence spectroscopy excited at 635 nm (in the $B^2\Sigma,v'=0-X^2\Sigma,v''=0$ band) and detected at 692 nm (within the $B,v'=0-X,v''=1$ band). Both a photomultiplier tube and a CCD camera were used. Due to the thermalization of molecular rotation, only a transition from the lowest rotational state could be detected at zero field, $N'=1,J'=3/2-N''=0,J''=1/2$. In the magnetic field this rotational transition splits into two features, one shifted towards lower and one towards higher frequencies. The measured shifts are linear in field strength and indicate a small difference ($0.02\mu_B$) in the magnetic moments between the ground and excited states. Here we present a theoretical analysis of the observed magnetic shifts. These are identified as arising from a rotational perturbation of the $B^2\Sigma,v'=0$ state by a close-lying $A^2\Pi,v'=1$ state that lends the $B$ state some of its $A$ character. We find that the Hamiltonian can be well approximated by a $3\times3$ matrix built out of elements that connect states from within the $\Sigma$-doublet and the $^3\Pi_{3/2}$ manifolds. The interaction parameter describing the $\Sigma-\Pi$ coupling in the Zeeman Hamiltonian is determined from the observed shifts and the field-free molecular parameters of CaH given by Berg and Klyning [Phys. Scr. 10, 331 (1974)] and by Martin [J. Mol. Spectrosc. 108, 66 (1984)]. © 1999 American Institute of Physics.
of the molecules that renders the population of higher rotational states negligible: the next rotational state lies 8.5 cm\(^{-1}\) above the \(N''=0, J''=1/2\) ground state and the intensity of the corresponding transition is well below 0.1\% of the \(N'=1, J'=3/2 \rightarrow N''=0, J''=1/2\) transition. This yields an upper limit on the rotational temperature of 1.5 K. Using absorption spectroscopy to calibrate the fluorescence detection, we found that up to \(10^{10}\) CaH molecules could, under certain conditions, be formed by a single ablation pulse. We were also able to detect the formation of \(X^2Σ, v''=1\) molecules which were about 10\(^{-10}\) fewer; their scarcity precluded them from being detected in the trap. However, we determined the upper limit of the \(v''=1 \rightarrow v'=0\) relaxation cross section (in collisions with the \(^3\)He buffer gas) to be \(10^{-18}\) cm\(^2\) which suggests that it should be possible to load them into the trap.

As the magnetic field is turned up, the field-free rotational transition is observed to split into two features shifted towards lower and higher frequencies. Figures 2a and 2b display, respectively, spectra with negative and positive frequency shifts taken at different values of \(H_{\text{edge}}\). All panels correspond to delay times of up to 25 ms (with respect to the ablation pulse). The frequency scale is relative to the frequency \(\nu_0=15762.96\,\text{cm}^{-1}\) of the \(R_1(1/2)\) field-free transition (Ref. 11). Part (a) shows spectra with a negative frequency shift corresponding to high-field seeking states; part (b) shows spectra with a positive frequency shift corresponding to low-field seeking states. All spectra are normalized to the peak height. Later times, the high-field seekers move towards the edge of the trap, hit the wall of the cell, stick to it and are lost; the low-field seekers, on the other hand, move towards the center of the trap and by 300 ms their distribution is that of a...
A correlation diagram between the low- and high-field limits for states from within the $X, v'=0$ and $B, v'=0$ manifolds; also shown are the perturbing states from within the $A, v'=1$ manifold (dashed). The states from within the $X$ and $B$ manifolds are labeled by the Hund’s case (b) angular momentum quantum numbers: $N$ (rotation) and $J$ (total, excluding nuclear spin) in the low-field limit and their projections on the direction of the field (the $Z$ axis), $M_N$ and $M$, in the high-field limit. The slopes of the eigenenergies in the high-field limit are determined by the projection, $M_S$, of the spin angular momentum on $Z$ (the Paschen-Back uncoupling). The states involved in the spectroscopic transitions detected in our experiment are shown by bold lines; note the different order of the eigenenergies in the $X$ and $B$ state manifolds in either limit—due to the opposite signs of the spin-rotation coupling constant. While the field dependence of the states correlating with $N''=0, J''=1/2$ from within the $X$-state manifold is trivial, given by $\pm g_S\hbar/2$ (with $g_S$ the electron spin gyromagnetic ratio) for $M''=\pm 1/2$, the Zeeman curves of the $N'=1, J'=3/2, M'=\pm 3/2, \pm 1/2$ states from within the $B^2\Sigma^+, \nu'=0$ state manifold are affected by a perturbation from the $A, \nu'=1$ state. Their computation is the subject of the following section.

II. THEORY: THE HAMILTONIAN AND ITS MATRIX ELEMENTS IN A BASIS SET INTERMEDIATE BETWEEN HUND’S CASES, (a) AND (b)

A. Field-free rotational perturbations

In the absence of an external field, the Hamiltonian of a linear molecule is given by the sum of the vibronic, rotational, spin-spin, and spin-orbit Hamiltonians (see Appendix):

$$H_0 = H_{v'v} + H_{r} + H_{ss} + H_{so}.$$  \hspace{1cm} (1)

In what follows we will consider the interaction of a $^2\Sigma, \nu_X$ with a $^2\Pi, \nu_{II}$ vibronic state. For this case, Hamiltonian (1) simplifies since $H_{ss}=0$, as in any doublet state. Hence, the $^2\Sigma, \nu_X \sim ^2\Pi, \nu_{II}$ perturbation (described by the off-diagonal matrix elements of $H_0$) is due to the vibronic overlap and the $L$- and $S$-uncoupling and spin-orbit interactions.

In order for two rotational states to interact, their total angular momenta (excluding nuclear spin), $J$, and their parities, $P$, must be the same and the overlap of the vibrational eigenfunctions of the two states must be nonzero. Therefore, to construct a suitable representation of the field-free Hamiltonian, we need a basis set of states with definite parity that correspond to the three electronic states in question: a $^2\Sigma$ state ($|\Omega|=1/2$) and two $^2\Pi$ states (one with $|\Omega|=1/2$ and one with $|\Omega|=3/2$). Such a basis set, describing an intermediate coupling between Hund’s cases (a) and (b), has been introduced by Radford and Broida:

$$\left\{ \begin{array}{c} c \frac{1}{d} J \end{array} \right\} = (2)^{-1/2} (2^2\Sigma_{1/2} \pm 2^2\Sigma_{-1/2}), \hspace{1cm} (2)$$

$$\left\{ \begin{array}{c} c \frac{2}{d} J \end{array} \right\} = a (2^2\Pi_{3/2} \pm 2^2\Pi_{-3/2}) - b (2^2\Pi_{1/2} \pm 2^2\Pi_{-1/2}), \hspace{1cm} (3)$$

$$\left\{ \begin{array}{c} c \frac{3}{d} J \end{array} \right\} = b (2^2\Pi_{3/2} \pm 2^2\Pi_{-3/2}) + a (2^2\Pi_{1/2} \pm 2^2\Pi_{-1/2}), \hspace{1cm} (4)$$

where

$$a = \frac{|X-(2-\lambda)|^{1/2}}{4X}, \hspace{1cm} (5)$$

$$b = \frac{|X-(2-\lambda)|^{1/2}}{4X}. \hspace{1cm} (6)$$
\[ \lambda = \frac{A}{B_{\Pi}}, \]  

\[ X = 4 \left( J + \frac{1}{2} \right)^2 + \lambda (\lambda - 4) \] \frac{1}{12},

and the upper and lower sign pertains respectively to the \( c \) and \( d \) symmetry. Note that \( |1, (c/d), J \rangle \rightarrow 2\Sigma_{1/2} \) and for \( \lambda \rightarrow -\infty, |2, (c/d), J \rangle \rightarrow 2\Pi_{3/2} \) and \( |3, (c/d), J \rangle \rightarrow 2\Pi_{1/2} \) ; for \( \lambda \rightarrow \infty, |2, (c/d), J \rangle \rightarrow 2\Pi_{1/2} \) and \( |3, (c/d), J \rangle \rightarrow 2\Pi_{3/2} \).

Using the matrix elements (A1)–(A8) of the Appendix, we obtain for the matrix elements of \( H \), see Eqs. (52),

\[ \left\langle \frac{c}{d}, J | H_0 | \frac{c}{d}, J \right\rangle = \alpha \pm \delta, \]  

\[ \left\langle \frac{c}{d}, J | H_0 | \frac{c}{d}, J \right\rangle = (2a^2 \gamma - 2ab \beta + b^2 \beta), \]  

\[ \left\langle \frac{c}{d}, J | H_0 | \frac{c}{d}, J \right\rangle = (2b^2 \gamma + 2ab \beta + a^2 \beta), \]  

\[ \left\langle \frac{c}{d}, J | H_0 | \frac{c}{d}, J \right\rangle = 2^{1/2} (a \eta \mp b (\xi \pm \theta)), \]  

\[ \left\langle \frac{c}{d}, J | H_0 | \frac{c}{d}, J \right\rangle = 2^{1/2} (b \eta + a (\theta \mp \xi)), \]  

\[ \left\langle \frac{c}{d}, J | H_0 | \frac{c}{d}, J \right\rangle = 2 [a^2 \beta + ab (\gamma - \beta) - b^2 \beta]. \]  

In this formulation, the dependence of the eigenstates of \( H_0 \) on the electronic motion and the nuclear vibration is contained in the parameters \( \xi = \xi(Q), \eta = \eta(Q), \) and \( \theta = \theta(Q,P) \) that depend on the perturbation parameters \( Q \) and \( P \), see Eqs. (A9) and (A10) of the Appendix.

\[ \lambda = \frac{A}{B_{\Pi}}, \]  

\[ X = 4 \left( J + \frac{1}{2} \right)^2 + \lambda (\lambda - 4) \] \frac{1}{12},

\[ \left\langle \frac{c}{d}, J | H_0 | \frac{c}{d}, J \right\rangle = \alpha \pm \delta, \]  

\[ \left\langle \frac{c}{d}, J | H_0 | \frac{c}{d}, J \right\rangle = (2a^2 \gamma - 2ab \beta + b^2 \beta), \]  

\[ \left\langle \frac{c}{d}, J | H_0 | \frac{c}{d}, J \right\rangle = (2b^2 \gamma + 2ab \beta + a^2 \beta), \]  

\[ \left\langle \frac{c}{d}, J | H_0 | \frac{c}{d}, J \right\rangle = 2^{1/2} (a \eta \mp b (\xi \pm \theta)), \]  

\[ \left\langle \frac{c}{d}, J | H_0 | \frac{c}{d}, J \right\rangle = 2^{1/2} (b \eta + a (\theta \mp \xi)), \]  

\[ \left\langle \frac{c}{d}, J | H_0 | \frac{c}{d}, J \right\rangle = 2 [a^2 \beta + ab (\gamma - \beta) - b^2 \beta]. \]  

B. Rotational perturbation in the presence of an external magnetic field

The Hamiltonian of a molecule subject to a uniform magnetic field \( \mathcal{H} \) is given by

\[ H = H_0 + H_Z, \]  

where the Zeeman Hamiltonian is

\[ H_Z = -\mu_B \mathcal{H}, \]  

see Eq. (A11) of the Appendix. The nonvanishing matrix elements of \( H_Z \) in the Radford-Broida basis set are:

\[ \left\langle 1, c, J | H_Z | 1, c, J \right\rangle = - \frac{M}{J + 1} \mu_B \mathcal{H}, \]  

\[ \left\langle 1, d, J | H_Z | 1, d, J \right\rangle = \frac{M}{J} \mu_B \mathcal{H}, \]  

\[ \left\langle \frac{c}{d}, J | H_Z | \frac{c}{d}, J \right\rangle = \left[ 1 + \frac{g_s}{2} \right] a^2 \frac{3 M}{J(J + 1)} + 2 g_s a b \mu_B \mathcal{H}, \]  

with

\[ t = \frac{[J(J + 1) - (\frac{1}{2})]^1/2}{J(J + 1)}, \]  

\[ u = \frac{J + (\frac{1}{2})}{J(J + 1)}. \]  

Note that the off-diagonal Zeeman matrix elements (21) and (23) modify the field-free perturbations given by the matrix elements (12) and (14). Also, note that states with the same \( c/d \) symmetry have the same parity but not vice versa.

Apart from the matrix elements that connect states with same \( J \) and \( M \) there are non-vanishing matrix elements between states with same \( M \) and parity but with \( J \)'s that differ by \( \Delta J = \pm 1 \). These matrix elements have always to be included for the other member of the \( \Sigma \)-doublet since members of a \( \Sigma \)-doublet are quasi-degenerate and have the same parity. On the other hand, in the case of a large spin-orbit splitting between the \( 2\Pi_{1/2} \) and \( 2\Pi_{3/2} \) states (or, more accurately, large \( \lambda \)), there can only be a significant interaction between the \( 2\Sigma_{1/2} \) state and just one of the \( 2\Pi \) states (the one that exhibits an accidental quasi-degeneracy with the \( 2\Sigma_{1/2} \) state). Therefore, the Hamiltonian can be well approximated by a \( 3 \times 3 \) matrix built out of elements that connect the \( \Sigma \)-doublet with either the \( 2\Pi_{1/2} \) or the \( 2\Pi_{3/2} \) state. Note that the other member of the \( 2\Pi_{1/2} \) or \( 2\Pi_{3/2} \) \( \Lambda \)-doublet does not interact with the three states because of its different parity.

Thus, in the case of a quasi-degeneracy, for given vibronic states and a given \( J \), between the \( 1, c, J, M \) and \( 2, c, J, M \) states of positive parity, the \( 3 \times 3 \) Hamiltonian matrix will also contain matrix elements that connect these two states with the \( 1, d, J + 1, M \) state:
\[
\begin{pmatrix}
\langle 1,d+1,M|H|1,d,J+1,M \rangle & \langle 1,d+1,M|H|1,c,J,M \rangle & \langle 1,d+1,M|H|2,c,J,M \rangle \\
\langle 1,c,J,M|H|1,d,J+1,M \rangle & \langle 1,c,J,M|H|1,c,J,M \rangle & \langle 1,c,J,M|H|2,c,J,M \rangle \\
\langle 2,c,J,M|H|1,d,J+1,M \rangle & \langle 2,c,J,M|H|1,c,J,M \rangle & \langle 2,c,J,M|H|2,c,J,M \rangle
\end{pmatrix}.
\] (26)

Or for a quasi-degeneracy between the \(|1,d,J,M\rangle\) and \(|3,d,J,M\rangle\) states of negative parity, the \(3 \times 3\) Hamiltonian matrix will also have matrix elements due to the \(|1,c,J-1,M\rangle\) state:

\[
\begin{pmatrix}
\langle 1,c,J-1,M|H|1,c,J-1,M \rangle & \langle 1,c,J-1,M|H|1,c,J,M \rangle & \langle 1,c,J-1,M|H|3,d,J,M \rangle \\
\langle 1,d,J,M|H|1,c,J-1,M \rangle & \langle 1,d,J,M|H|1,c,J,M \rangle & \langle 1,d,J,M|H|3,d,J,M \rangle \\
\langle 3,d,J,M|H|1,c,J-1,M \rangle & \langle 3,d,J,M|H|1,c,J,M \rangle & \langle 3,d,J,M|H|3,d,J,M \rangle
\end{pmatrix}.
\] (27)

The mixed-J matrix elements occur only for the Zeeman part of the Hamiltonian and can be derived from Eqs. (A23)–(A30) and (A31)–(A36) of the Appendix. For the above examples these are:

\[
\langle 1,d+1,M|H|1,c,J,M \rangle = g_S \frac{(J+\frac{1}{2})(J+\frac{1}{2})(J+M+1)(J-M+1)^{1/2}}{(J+1)[(2J+1)(2J+3)]^{1/2}} \mu_B \mathcal{H},
\] (28)

\[
\langle 1,d+1,M|H|2,c,J,M \rangle = 2^{-1/2} b L_{\Pi,\Sigma}
\]

\[
\times \frac{(J+\frac{1}{2})(J+\frac{1}{2})(J+M+1)(J-M+1)^{1/2}}{(J+1)[(2J+1)(2J+3)]^{1/2}} \mu_B \mathcal{H} + 2^{-1/2} a L_{\Pi,\Sigma}
\]

\[
\times \frac{(J+\frac{1}{2})(J-\frac{1}{2})(J+M+1)(J-M+1)^{1/2}}{(J+1)[(2J+1)(2J+3)]^{1/2}} \mu_B \mathcal{H},
\] (32)

\[
\langle 1,c,J-1,M|H|1,d,J,M \rangle = g_S \frac{(J+\frac{1}{2})(J-\frac{1}{2})(J+M)(J-M)}{J[(2J+1)(2J-1)]^{1/2}} \mu_B \mathcal{H},
\] (33)

\[
\langle 1,c,J-1,M|H|3,d,J,M \rangle = 2^{-1/2} L_{\Pi,\Sigma} a \frac{(J+\frac{1}{2})(J-\frac{1}{2})(J+M)(J-M)}{J[(2J+1)(2J-1)]^{1/2}} \mu_B \mathcal{H} + 2^{-1/2} L_{\Pi,\Sigma} b \frac{(J+\frac{1}{2})(J+\frac{1}{2})(J+M)(J-M)}{J[(2J+1)(2J-1)]^{1/2}} \mu_B \mathcal{H}.
\] (35)

In the present case of the CaH molecule, the \(N'=1\) states with \(J'=3/2\) and \(1/2\) from within the \(B^2 \Sigma, v'=0\) state manifold are perturbed by the close-lying \(J'=3/2\) state from within the \(A^2 \Pi_{\Sigma}, v'=1\) manifold (whose spin-orbit coupling constant, \(A>0\)). Hence the interacting states have negative parity and the relevant \(3 \times 3\) Hamiltonian matrix takes the form of Eq. (27).

III. COMPARISON OF THEORY AND EXPERIMENT

Figure 4 shows the measured (points) spectral shifts (as derived from the positions of the maxima of the distribution curves of Fig. 2) as a function of the magnetic field strength at the edge of the trap, \(\mathcal{H}_{\text{edge}}\). The shifts are linear in field strength and correspond to a small difference (0.02 \(\mu_B\)) in the magnetic moments between the ground and excited states. Taking the field-free parameters of CaH from Berg and Klyning and Martin (see caption) and approximating \(L_{\Pi,\Sigma}=\langle \Pi|L^+|\Sigma \rangle \) by \(2\langle \Pi|B_L|\Sigma \rangle/B_S=2 Q/B_S\) we obtained Zeeman curves for the \(N'=1, J'=3/2, M'=\pm 3/2\) that, after subtraction of the respective \(N''=0, J'=1/2, M'=\pm 1/2\) curves, yield a semiquantitative agreement with the observed Zeeman shifts (dashed lines). The positive Zeeman shift corresponds to the transition between the \(N''=0, J''=1/2, M''=1/2\) and the negative shift to the transition between the \(N''=0, J''=1/2, M''=1/2\) and the \(N'=1, J'=3/2, M'=3/2\) state. By fitting the calculated Zeeman shifts to the observed ones (full lines) we obtain \(L_{\Pi,\Sigma}=0.4\). This value is about twice that of \(2 Q/B_S\), i.e., quite at odds with the "pure precession" hypothesis, see, e.g., Refs. 14 and 17. The analysis of extensive field-free spectra of CaH (Refs. 6, 7) led earlier to a similar conclusion.

The calculated slope of the negative Zeeman shift is slightly steeper than that of the positive shift; this is due to...
the enhanced repulsion of the $N'=1, J'=3/2, M'=3/2$ state that lies closer to the perturbing $A$-state.

We note that a field-induced hybridization of $J$ may lead to the loss of a definite parity of the states, thus weakening the parity selection rule for the perturbation.\(^\text{15}\) We neglected this effect in our calculations.

IV. CONCLUSIONS

We have observed splitting of the $B^2\Sigma_v^o=0(N'=1, J'=3/2)\rightarrow X^2\Sigma_v^o=0(N''=0, J''=1/2)$ transition of CaH in a magnetic trapping field. Theory to explain the observed splitting has been developed. A good agreement between the theory and our experiment has been found. We conclude that the splitting is due to the coupling of the $N'=1$ states from within the $B^2\Sigma_v^o=0$ state manifold with the close-lying $J'=3/2$ state from within the $A^2\Pi_{3/2}, v'=1$ manifold. The mixing of the $B$ and $A$-states results in a modification of the $B$-state magnetic dipole moment (and other properties). Fitting of the experimental magnetic shifts yields a value $L_{\Pi,S}=0.4$ of the interaction parameter that describes the coupling between the $B$ and $A$ states. This is about twice the value predicted by the “pure precession” hypothesis.\(^\text{17}\)

ACKNOWLEDGMENTS

We thank R.W. Field (MIT) for enlightening discussions on rotational perturbations and the Zeeman effect in CaH. This material is based upon work supported by the National Science Foundation under Grant No. PHY-9511951. J.D.W. is supported by a National Science Foundation Graduate Research Fellowship.

APPENDIX

1. The field-free Hamiltonian and its matrix elements in Hund’s case (a) basis

The matrix elements of the field-free Hamiltonian of a linear molecule in the Hund’s case (a) basis that couple the $2\Sigma$ and $2\Pi$ states in question, first given by van Vleck,\(^\text{16}\) are reproduced here for convenience:

\[
\begin{align*}
\langle 2\Sigma_{1/2}\mid H_0 \mid 2\Sigma_{1/2}\rangle &= \langle 2\Sigma_{1/2}\mid H_0 \mid 2\Sigma_{1/2}\rangle \\
&= B_{\Sigma}(J(J+1) + \frac{1}{2}) + \Delta E = \alpha, \quad (A1) \\
\langle 2\Pi_{1/2}\mid H_0 \mid 2\Pi_{1/2}\rangle &= \langle 2\Pi_{1/2}\mid H_0 \mid 2\Pi_{1/2}\rangle \\
&= B_{\Pi}(J(J+1) + \frac{1}{2}) - \frac{A}{2} = \beta, \quad (A2) \\
\langle 2\Pi_{3/2}\mid H_0 \mid 2\Pi_{3/2}\rangle &= \langle 2\Pi_{3/2}\mid H_0 \mid 2\Pi_{3/2}\rangle \\
&= B_{\Pi}(J(J+1) - \frac{1}{2}) + \frac{A}{2} = \gamma, \quad (A3) \\
\langle 2\Sigma_{1/2}\mid H_0 \mid 2\Sigma_{1/2}\rangle &= \langle 2\Sigma_{1/2}\mid H_0 \mid 2\Sigma_{1/2}\rangle \\
&= B_{\Sigma}(J+\frac{1}{2}) = (-1)^s \delta, \quad (A4) \\
\langle 2\Pi_{3/2}\mid H_0 \mid 2\Pi_{3/2}\rangle &= \langle 2\Pi_{3/2}\mid H_0 \mid 2\Pi_{3/2}\rangle \\
&= B_{\Pi}(J-\frac{1}{2})(J+\frac{1}{2}) = \epsilon, \quad (A5) \\
\langle 2\Pi_{1/2}\mid H_0 \mid 2\Sigma_{1/2}\rangle &= \langle 2\Pi_{1/2}\mid H_0 \mid 2\Sigma_{1/2}\rangle \\
&= 2Q(J+\frac{1}{2}) = (-1)^s \xi, \quad (A6) \\
\langle 2\Pi_{3/2}\mid H_0 \mid 2\Sigma_{1/2}\rangle &= \langle 2\Pi_{3/2}\mid H_0 \mid 2\Sigma_{1/2}\rangle \\
&= 2Q(J-\frac{1}{2})(J+\frac{1}{2}) = \eta, \quad (A7) \\
\langle 2\Sigma_{1/2}\mid H_0 \mid 2\Pi_{1/2}\rangle &= \langle 2\Sigma_{1/2}\mid H_0 \mid 2\Pi_{1/2}\rangle \\
&= 2P = \theta, \quad (A8)
\end{align*}
\]

with $\Delta E$ the energy difference between the zero-point energies of the $\Sigma$ and $\Pi$ states, $B_{\Sigma}$ and $B_{\Pi}$ their respective rotational constants, $A$ the spin-orbit splitting constant of the $\Pi$ state, and

\[
\begin{align*}
P &= \langle \Pi\mid [\mathbf{A}\mathbf{L}_s]\mid |\Sigma\rangle = \frac{1}{2}\langle \Pi\mid [\mathbf{A}\mathbf{L}^+]\mid |\Sigma\rangle, \quad (A9) \\
Q &= \langle \Pi\mid [\mathbf{B}\mathbf{L}_s]\mid |\Sigma\rangle = \frac{1}{2}\langle \Pi\mid [\mathbf{B}\mathbf{L}^+]\mid |\Sigma\rangle. \quad (A10)
\end{align*}
\]

the rotational perturbation parameters; $s=0$ or 1 depending on whether the $\Lambda=0$ state is $\Sigma^+$ or $\Sigma^-$. 

2. The Zeeman Hamiltonian and its matrix elements in Hund’s case (a) basis

The Zeeman Hamiltonian is given by

\[
H_\Sigma = -\mu_Z H_z, \quad (A11)
\]

with $\mu_Z$ the component of the molecular magnetic dipole moment operator along the space-fixed $Z$-axis whose direction is determined by $H_z$. The magnetic dipole moment operator
\[ \mu_Z = \frac{1}{2} (\Phi_Z^+ \mu^- + \Phi_Z^- \mu^+) + \Phi_Z^0 \mu_z \]  
(A12)

depends on the body-fixed magnetic dipole moment operators
\[ \mu_{\pm} = -(g_L L_{\pm} + g_S S_{\pm}) \mu_B, \]  
(A13)
\[ \mu_z = -(g_L L_z + g_S S_z) \mu_B \]  
(A14)

(with \( g_L = 1 \) and \( g_S = 2.0023 \) the orbital and spin gyromagnetic ratios and \( \mu_B \) the Bohr magneton) and the direction cosine operator \( \Phi \) with components
\[ \Phi^\pm = \mathbf{F} \cdot \mathbf{g}, \]  
(A15)

where \( \mathbf{F} = \mathbf{X}, \mathbf{Y}, \mathbf{Z} \) and \( \mathbf{g} = \mathbf{x}, \mathbf{y}, \mathbf{z} \) are unit vectors defining right-handed Cartesian space- and body-fixed coordinate systems.

As a result,
\[ H_Z = \left[ \frac{1}{2} (\Phi_Z^+ \mathbf{L}^+ + \Phi_Z^- \mathbf{L}^-) + \Phi_Z^0 \mathbf{L} \right] \mu_B \mathcal{H} \]  
(A16)
\[ + \left[ \frac{1}{2} (\Phi_Z^+ \mathbf{S}^+ + \Phi_Z^- \mathbf{S}^-) + \Phi_Z^0 \mathbf{S} \right] g_S \mu_B \mathcal{H} \]  
(A17)
\[ = (L_Z + g_S S_Z) \mu_B \mathcal{H}. \]  
(A18)

The Hund’s case (a) matrix elements of \( \mathbf{L} \) and \( \mathbf{S} \) in the body-fixed, nonrotating frame are
\[ \langle L \Lambda \pm 1 \Sigma | L \Sigma \rangle = \langle \Lambda \pm 1 | \Lambda \rangle \]  
(A19)
\[ \langle L \Lambda \Sigma | L \Lambda \Sigma \rangle = \langle \Lambda \Sigma | \Lambda \Sigma \rangle \]  
(A20)
\[ \langle L \Lambda \Sigma | L \Lambda \Sigma \rangle = \Lambda \]  
(A21)
\[ \langle L \Lambda \Sigma | S \rangle \langle S \Lambda \Sigma \rangle = 0 \]  
(A22)

As a result, for the states of interest:
\[ \langle 2 \Sigma \pm 1/2 | L \pm 1/2 \rangle = \pm \frac{1}{2}, \]  
(A23)
\[ \langle 2 \Sigma \pm 1/2 | S \pm 1/2 \rangle = \langle 2 \Sigma \pm 1/2 | L \pm 1/2 \rangle = \pm \frac{1}{2}, \]  
(A24)
\[ \langle 2 \Pi \pm 1/2 | S \pm 1/2 \rangle = \langle 2 \Pi \pm 1/2 | L \pm 1/2 \rangle = \pm \frac{1}{2}, \]  
(A25)
\[ \langle 2 \Pi \pm 1/2 | S \rangle \langle S \pm 1/2 \rangle = \pm \frac{1}{2}, \]  
(A26)
\[ \langle 2 \Pi \pm 1/2 | L \rangle \langle L \pm 1/2 \rangle = \pm \frac{1}{2}, \]  
(A27)
\[ \langle 2 \Pi \pm 1/2 | L \pm 1/2 \rangle = \pm \frac{1}{2}, \]  
(A28)
\[ \langle 2 \Sigma \pm 1/2 | L \pm 1/2 \rangle = \langle 2 \Sigma \pm 1/2 | L \pm 1/2 \rangle = \pm 1, \]  
(A29)
\[ \langle 2 \Pi \pm 1/2 | L \pm 1/2 \rangle = \pm \frac{1}{2}, \]  
(A30)

The direction cosine matrix elements along the space-fixed \( Z \)-axis can be obtained from Hougen’s table
\[ \Delta \Omega = \pm 1, \Delta J = \Delta M = 0: \]  
\[ \langle \Omega \pm 1JM | \Phi_Z^0 \Omega JM \rangle = \left\{(J \mp \Omega)(J \pm \Omega + 1)\right\}^{1/2} \]  
\[ \frac{1}{J(J + 1)} \mu_B \mathcal{H}; \]  
(A31)
\[ \Delta \Omega = \pm 1, \Delta J = + 1, \Delta M = 0: \]  
\[ \langle \Omega \pm 1JM | \Phi_Z^0 \Omega JM \rangle = \left\{(J \mp \Omega)(J \pm \Omega + 1)(J + M + 1)(J - M + 1)\right\}^{1/2} \]  
\[ \frac{1}{(J + 1)(2J + 1)(2J + 3)} \mu_B \mathcal{H}; \]  
(A32)
\[ \Delta \Omega = \pm 1, \Delta J = - 1, \Delta M = 0 \]  
\[ \langle \Omega \pm 1JM | \Phi_Z^0 \Omega JM \rangle = \left\{(J \mp \Omega)(J \mp \Omega - 1)(J + M)(J - M)\right\}^{1/2} \]  
\[ \frac{1}{J(J - 1)(2J - 1)} \mu_B \mathcal{H}; \]  
(A33)
\[ \Delta \Omega = 0, \Delta J = 0 \]  
\[ \langle \Omega \Omega | \Phi_Z^0 \Omega \Omega \rangle \]  
\[ \langle \Omega \Omega | \Phi_Z^0 \Omega \Omega \rangle = \frac{\Omega M}{J(J + 1)} \]  
(A34)
\[ \Delta \Omega = 0, \Delta J = 1, \Delta M = 0 \]  
\[ \langle \Omega J-M | \Phi_Z^0 \Omega J-M \rangle \]  
\[ \langle \Omega J-M | \Phi_Z^0 \Omega J-M \rangle = \frac{1}{J(J + 1)(2J + 3)} \frac{(J + M + 1)(J - M + 1)}{(J + 1)(2J + 1)} \mu_B \mathcal{H}; \]  
(A35)
\[ \Delta \Omega = 0, \Delta J = - 1, \Delta M = 0 \]  
\[ \langle \Omega J-M | \Phi_Z^0 \Omega J-M \rangle \]  
\[ \langle \Omega J-M | \Phi_Z^0 \Omega J-M \rangle = \frac{1}{J(J - 1)(2J - 1)} \mu_B \mathcal{H}; \]  
(A36)

Hence, for instance
\[ \langle 2 \Sigma_{1/2}, J-1, M | H_Z | 2 \Pi_{3/2}, J, M \rangle \]  
\[ \langle 2 \Sigma_{1/2}, J-1, M | H_Z | 2 \Pi_{3/2}, J, M \rangle \]  
\[ = -L_{\Pi, \Sigma} \frac{1}{2J(2J + 1)} \frac{[(J + \frac{1}{2})(J + \frac{1}{2})(J + M)(J - M)]^{1/2}}{\mu_B \mathcal{H}}. \]  
(A37)


18 R. N. Zare, Angular Momentum (Wiley, New York, 1988).