The Microwave Spectrum of Silylisothiocyanate, SiH₃NCS

II. rₐ-Structure, Dipolmoment and ¹⁴N-quadrupole Coupling Constant. A Contribution to the Study of the SiN-bond

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The microwave spectra of ¹⁵N- and ¹³C-substituted SiH₃NCS were recorded in the frequency region between 8 and 40 GHz. Combining the resulting rotational constants with values obtained previously for other isotopic species, the complete rₐ-structure of the heavy atom chain could be determined. This leads to the following rₐ-bond distances: rₐ₁-N = 1.574Å, rₐ₂-C = 1.220Å, and rₐ₃-N = 1.672Å. From Stark effect splittings the electric dipole moment of the most abundant species was determined for the ground vibrational state and for the first excited state of the lowest frequency bending vibration ν₁₀. The values are (ν₁₀ = 0 | μₐ | ν₁₀ = 0) = 2.38 ± 0.02 D, and (ν₁₀ = 1, l = 1 | μₐ | ν₁₀ = 1, l = 1) = 2.36 ± 0.02 D. The direction of the dipole moment is discussed. From the quadrupole hyperfine structure of the rotational transitions the ¹⁴N-quadrupole coupling constant could be determined as ²ζ₂z = 0.75 MHz. The experimental results are compared to CNDO/2 calculations.

Introduction

Silylisothiocyanate provides an interesting example for the study of the SiN-bond. As is known since the work of Kewley et al.¹,² the molecule is a symmetric top with a linear arrangement of the heavy atom chain. This result may appear surprising at first sight, since the simple nonpolar valence formula (I) with an sp² hybridized nitrogen atom would imply a bent structure. (Such a bent structure has indeed been found for the related molecule HNC with a bond-angle < H-N-C = 135°.³)

(I)  
\[ \text{H}_3\text{Si} = \text{N} = \text{C} = \text{S} \]  
\[ \overline{\text{N}} = \text{C} = \text{S} \]

(II)  
\[ \text{H}_3\text{Si} = \text{N} = \text{C} = \text{S} \]  
\[ \overline{\text{N}} = \text{C} = \text{S} \]

(III)  
\[ \text{H}_3\text{Si} - \text{N} = \overline{\text{C}} = \text{S} \]

It is however possible to draw two more valence formulae (II) and (III), both highly polar, which would favour the observed linear arrangement of the Si-N-C-S-chain. Since the limiting mesomer forms (II) and (III) would lead to different bond distances and to opposite polarities of the molecular electric dipole moment, it was desirable to determine a complete rₐ-structure of the Si-N-C-S-chain together with the electric dipole moment. We therefore analyzed the microwave rotational spectra of two more isotopes, H₃²⁶Si¹⁵N¹³C¹⁸S and H₃²⁸Si¹⁴N¹³C¹⁸S, yielding accurate rotational constants B₀ and centrifugal distortion constants Dᵢ and Dᵢⱼ for both isotopes. Furthermore vibronic expectation values for the z-component of the molecular electric dipole moment were determined for the vibrational ground state and for the first excited state of the degenerate bending vibration ν₁₀. (The z-axis points into the direction of the molecular symmetry axis.) In addition we have analyzed the ¹⁴N nuclear quadrupole hyperfine structure of the rotational transitions, which provides information on the immediate electronic environment of the ¹⁴N nucleus. A discussion of the experimental results, including a comparison with the results of CNDO-calculations, is given at the end of this paper.

Experimental

The samples were prepared by streaming H₃²⁶SiBr-vapour through tubes packed with Ag²⁶Si²⁶SiCl²⁶Cl resp. The latter compounds were prepared by smelting K²⁶Cl²⁶Cl (K²⁶Cl²⁶Cl) with sulfur, taking up the melt in dilute H₂SO₄ and precipitating Ag²⁶Si²⁶SiCl²⁶Cl by addition of AgNO₃. Since H₃₂SiNCS readily reacts with water, rests of water adsorbed to the walls of the waveguide absorption cell had to be removed by pumping the cell at +90°C for several days. The spectra were recorded with a microwave spectrometer of the Hughes-Wilson type, as previously described. Phase stabi-
lized BWO’s as radiation sources and 33 kHz square wave Stark effect modulation were used throughout. Double width X-band absorption cells were used to provide a sufficiently uniform Stark-field over the absorption volume. Typical recording conditions were: sample pressures about 5 mTorr and cell temperatures about –65 °C. For the dipole moment determinations involving first order Stark-effects, the standard Square wave generator was replaced by a function generator (Hp 8005A) in order to provide high quality zero based squares below 10 V, peak to peak.

For the vibrational ground state the energy levels of the effective rotational Hamiltonian may be approximated as:

$$ W_{JK} = \hbar [B_0 (J(J+1) - K^2) + A K^2 - D_K K^4 - D_J J^2 (J+1)^2 - D_{JK} J (J+1) K^2] + W_{\text{HFS}}. $$

In Eq. (1) $B_0$ is the effective rotational constant for the ground vibrational state. $D_K$, $D_J$ and $D_{JK}$ are small centrifugal distortion constants. $J$ and $K$ are the quantum numbers for the square of the overall angular momentum, $\langle J^2 \rangle = \hbar J (J+1)$, and the component of the angular momentum in direction of the molecular symmetry axis, $\langle P_z \rangle = \hbar K$. $W_{\text{HFS}}$ stands for the $^{14}$N nuclear quadrupole hyperfine contribution. In Silylisothiocyanate it is rather small and may be neglected for higher $J$ transitions (see below).

Since there is no electric dipole moment component perpendicular to the molecular symmetry axis in the vibrational ground state, the electric field vector of the incident microwave radiation has no lever to produce a torque about the figure axis and $K$ is left constant during transitions. For $J$ quantum mechanics leads to the electric field dipole selection rule $\Delta J = \pm 1$. Thus neglecting the $^{14}$N hyperfine contribution for a moment Eq. (1) leads to the following frequency expression which was used to fit $B_0$, $D_J$ and $D_{JK}$ to the observed spectra by a least squares procedure.

$$ \nu_{J,K \rightarrow J+1,K} = 2B_0 (J+1) - 4D_J (J+1)^3 - 2D_{JK} (J+1) K^2. $$

Table 1. Microwave spectra of $^{13}$C and $^{15}$N substituted Silylisothiocyanate. The observed frequencies (MHz) are compared to the values calculated from the molecular constants listed in Table 2 according to Equation (2).

<table>
<thead>
<tr>
<th>$\text{SiH}_3\text{N}^{13}\text{C}$</th>
<th>$J \rightarrow J'$</th>
<th>8 $\rightarrow$ 9</th>
<th>9 $\rightarrow$ 10</th>
<th>10 $\rightarrow$ 11</th>
<th>11 $\rightarrow$ 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K$</td>
<td>obs</td>
<td>o – c</td>
<td>obs</td>
<td>o – c</td>
<td>obs</td>
</tr>
<tr>
<td>0</td>
<td>27254.83</td>
<td>0.00</td>
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<td>0.00</td>
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<tr>
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<td>0.00</td>
<td>30269.66</td>
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<tr>
<td>8</td>
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<td>—</td>
<td>33252.52</td>
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<tr>
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<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>33236.91</td>
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</table>

<table>
<thead>
<tr>
<th>$\text{SiH}_3\text{N}^{15}\text{N}$</th>
<th>$J \rightarrow J'$</th>
<th>8 $\rightarrow$ 9</th>
<th>9 $\rightarrow$ 10</th>
<th>10 $\rightarrow$ 11</th>
<th>11 $\rightarrow$ 12</th>
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<tbody>
<tr>
<td>$K$</td>
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<td>o – c</td>
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<td>—</td>
<td>33241.32</td>
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</table>
Table 2. Rotational constants and centrifugal distortion constants of silylisothiocyanate. The values for the $^{13}$C- and $^{15}$N-isotopic species result from a least squares fit to the spectra listed in Table 1. The values for the most abundant species are taken from the work of Dössel and Robiette.

<table>
<thead>
<tr>
<th>Isotopic species</th>
<th>$B_0$/MHz</th>
<th>$D_{JK}$/kHz</th>
<th>$D_{J}/$kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{28}\text{Si}^{14}\text{N}^{13}\text{C}^{32}\text{S}$</td>
<td>1516.040(1)</td>
<td>41.958(6)</td>
<td>0.087(4)</td>
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<tr>
<td>$^{28}\text{Si}^{14}\text{N}^{15}\text{C}^{32}\text{S}$</td>
<td>1514.552(1)</td>
<td>42.30(1)</td>
<td>0.086(6)</td>
</tr>
<tr>
<td>$^{28}\text{Si}^{14}\text{N}^{13}\text{C}^{32}\text{S}$</td>
<td>1514.169(1)</td>
<td>41.76(1)</td>
<td>0.074(6)</td>
</tr>
</tbody>
</table>

(Numbers in brackets give one standard deviation in units of the last significant figure.)

The $r_s$-Structure of the Si—N—C—S Chain

From the differences in the $B_0$-values for the $^{15}$N- and $^{13}$C-isotopes with respect to the $B_0$ value of the most abundant species it is possible to determine the center of mass distances of the substituted atoms (referred to the center of mass of the most abundant species) via

$$r_s = \sqrt{(I'_{\perp} - I_{\perp})/m}.$$  

In Eq. (3) the symbols have the following meaning:

$I_{\perp} = \frac{\hbar}{2\pi} r^2 B_0$ is the molecular moment of inertia about the principal inertia axis perpendicular to the symmetry axis. The prime indicates the substituted species.

$m = [M \Delta M/(M + \Delta M)]$ with $M =$ molecular mass of the unsubstituted species and $\Delta M = M' - M$ the change of the molecular mass upon substitution.

Equation (3) follows from the rigid rotor model with atomic masses located at the positions of the nuclei. Since only the difference of the effective moments of inertia enters into the expression, vibrational effects cancel largely and the deviations of the $r_s$-values from the equilibrium values, $r_e$, are usually below $0.005 \text{ Å}$.

With the $B_0$ values given in Tab. 2 the Eq. (3) leads to the following center of mass distances for nitrogen and carbon respectively:

$$r_{s(N)} = 0.5764(2) \text{ Å}, \quad r_{s(C)} = 0.6444(2) \text{ Å}.$$  

The numbers in brackets give one standard deviation calculated from the experimental uncertainties in the $B_0$ values i.e. they do not include estimates on possible vibrational effects causing deviations of the $r_s$ values from the corresponding equilibrium values! Now using the $r_s$-distances determined by Dössel and Robiette for silicon and sulfur, all bond distances in the Si—N—C—S-chain can be calculated. The resulting complete $r_s$-structure is given in Fig. 1 where the data for the Silyl-group are taken from the work of Kewley et al.

The Molecular Electric Dipole Moment

The absolute value of the vibrational ground state expectation value of the molecular electric dipole moment was determined from the first order

Table 3. Vibrational ground state Stark satellites for the $K=3$, $J = 3 \rightarrow J' = 4$ and $K = 0$, $J = 2 \rightarrow J' = 3$ rotational transitions of the most abundant isotopic species.

<table>
<thead>
<tr>
<th>Rotational transition</th>
<th>Electric $M_J$ Stark field</th>
<th>Rotational transition</th>
<th>Electric $M_J$ Stark field</th>
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<tbody>
<tr>
<td>$K=3$, $J = 3 \rightarrow J' = 4$</td>
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<td>$K=0$, $J = 2 \rightarrow J' = 3$</td>
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Stark-effect of the $|K| = 3, J = 3 \rightarrow J' = 4$ transition and from the second order Stark-effect of the $K = 0, J = 2 \rightarrow J' = 3$ transition of the most abundant isotopic species (see Table 3). The spectrometer was calibrated using OCS with $\langle 0 | \mu _z | 0 \rangle = 0.71521$ D as standard. With $\langle 0 | \mu _z | 0 \rangle = 2.370(20)$ D from $|K| = 3, J = 3 \rightarrow J' = 4$ and with $\langle 0 | \mu _z | 0 \rangle = 2.389(20)$ D from $K = 0, J = 2 \rightarrow J' = 3$ we give the vibrational ground state expectation value as $\langle 0 | \mu _z | 0 \rangle = 2.38 \pm 0.02$ Debye.

In order to get experimental information on the dependence of the electric dipole moment on the bending of the heavy atom chain during the degenerate $v_{10}$ bending motion, we also investigated the Stark effect of the $|K| = 1, J = 2 \rightarrow J' = 3$ 1-type doublet in the first excited state $v_{10} = 1$. The zero field 1-doublet splitting is $16.665(20)$ MHz.

Equation (4) holds as long as off-diagonal Stark-effect matrix elements which connect nondegenerate levels (i.e. levels which differ in their $J$ and $K$ values) may be neglected.

Since we feel that the presentation in Ref. 15 might lead to the wrong impression that further approximations need to be made which limit the applicability of Equation (4), the derivation of Eq. (4) is sketched in the Appendix. From the experimental values given in Figure 2 the Eq. (4) leads to the excited state expectation value of $\langle v_{10} = 1 | \mu _z | v_{10} = 1 \rangle = 2.36 \pm 0.02$ D i.e. there is essentially no change with respect to the ground state expectation value.

### $^{14}$N Hyperfinestructure

Due to the nonspherical Coulomb potential well at the position of the “prolate” $^{14}$N nucleus, the latter tends to align itself with respect to the well. This leads to a weak coupling of nuclear spin, $I$, and molecular rotation and causes a first order splitting of the rotational levels according to Equation (5). The hyperfine coupling constant with $e$ the electronic charge, $Q = 0.01 \cdot 10^{-24}$ cm$^2$ 17 the nuclear quadrupole moment of the $^{14}$N-nucleus and $\nabla^2 V'/\nabla z^2$ the second derivative of the Coulomb potential in direction of the molecular axis. The prime indicates that only the Coulomb potential due to the charge distribution outside a small sphere around the nucleus enters into the expression for the quadrupole coupling constant.

From Eq. (5) and the additional F-selection rule, $\Delta F = 0, \pm 1$, it may be shown that the largest hfs-splittings of the rotational absorption lines should
occur for the $|K| = 2, J = 2 \rightarrow J' = 3$ and $|K| = 3, J = 3 \rightarrow J' = 4$ transitions. The splitting of the $J = 2 \rightarrow J' = 3$ transition is shown in Fig. 3 together with computer simulation using the value $\chi_{zz} = +0.75 \text{ MHz}$ and a Lorentzian lineshape function with a halfintensity halfwidth of 50 kHz. Modulation- and wall-broadening are the dominant terms which determine this line width. Only the latter is reproduced by a Lorentzian lineshape function. Modulation broadening is responsible for the “triangle form” of the lines. The observed spectrum is extremely sensitive to minor offsets of the basis of the modulating Stark field. Due to the small quadrupole coupling constant, Stark fields on the order of 0.2 V/cm are already sufficient for effectively mixing the hyperfine states, shifting the levels, and changing the selection rules. This effect is illustrated in the computer simulations shown in Fig. 4. In the case of the $|K| = 3, J = 3 \rightarrow J' = 4$ transition a higher Stark field ($E$ on the order of 80 V/cm) is needed to separate the zero field quadrupole hyperfine spectrum from the Stark-quadrupole spectra of the nearby $|K| = 1$ and $|K| = 2$ lines. Since our high quality square wave generator was only capable of delivering square waves up to 10 V peak to peak, the $|K| = 3, J = 3 \rightarrow J' = 4$ transition could not be used for the fit. From the observed spectrum (Fig. 3) and the experience with computer simulations using different $\chi_{zz}$ values and zero-offsets we estimate the uncertainty of the quadrupole coupling constant to be on the order of $\pm 0.05 \text{ MHz}$.

For the higher $J$ transitions the hfs-splittings drop below the resolution power of our spectrometer. This is especially true for the transitions listed in Tab. 1, which were used for the fit of the rotational constants of the $\text{H}_3\text{Si}^{14}\text{N}^{13}\text{CS}$ species.

**Discussion**

The experimental results reported above may be used to get some insight into the bonding situation in silylisothiocyanate. We first discuss the bonding in terms of the two mesomer forms (II) and (III). From the Pauling electronegativities of the elements and the observed bond distances we expect dipole moments of $\mu_z = 4.2 \text{ D}$ (Si negative) for form (II), and of $\mu_z = -14.4 \text{ D}$ (S negative) for form (III) (compare Figure 5). Thus the observed absolute value of $|\langle | \mu_z | \rangle | = 2.38 \text{ D}$ might result from a 90% to 10% mixture of forms (II) and (III) leading to $\mu_z = +2.38 \text{ D}$ (Si negative), or from a 65% to 35% mixture leading to $\mu_z = -2.38 \text{ D}$ (S negative). For both choices form (II), which implies a Si = N-double bond, contributes considerably. Thus the observed dipole moment indicates that the Si-d orbitals do considerably contribute to the occupied molecular orbitales.

The first excited state expectation value of $\langle | \mu_z | \rangle$ gives information on the dependance of $\mu_z$ on the bending motion. From the coincidence of the ground state and first excited state expectation values of $\mu_z$
we conclude that $\mu_z$ remains essentially constant over the bending motion, that is up to an angle of about $20^\circ$ between the SiN-bond and the CS-bond. This value follows from the observed frequency $\tilde{v}_{10} = 54$ cm$^{-1}$ and a “reduced mass” on the order of 50 amu Å$^2$ as the square root of the harmonic oscillator expectation value for the square of the bending angle. We now turn to the bond distances. Using Pauling’s covalent bond radii listed in Tab. 4 and applying a “bent bond correction” of $-0.02$ Å for the $r_{\text{SiN}}$ and $r_{\text{CS}}$ distances and of $-0.04$ Å for the central N–C bond, the following bond distances are obtained for the limiting structures:

<table>
<thead>
<tr>
<th></th>
<th>$r_{\text{SiN}}$</th>
<th>$r_{\text{N–C}}$</th>
<th>$r_{\text{CS}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(II) $\text{H}_3\text{Si}=\text{N}=\text{C}=\text{S}$</td>
<td>1.57 Å</td>
<td>1.21 Å</td>
<td>1.58 Å</td>
</tr>
<tr>
<td>(III) $\text{H}_3\text{Si}=\text{N}=\text{C}–\text{S}$</td>
<td>1.79 Å</td>
<td>1.07 Å</td>
<td>1.79 Å</td>
</tr>
<tr>
<td>observed values</td>
<td>1.673 Å</td>
<td>1.221 Å</td>
<td>1.575 Å</td>
</tr>
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</table>

As is seen, the $r_{\text{N–C}}$ and $r_{\text{CS}}$ distances are practically those predicted for a pure form (II), while the $r_{\text{SiN}}$ distance turns out to lie between a single bond and a double bond distance. This indicates that the simple concepts upon which the above bond distance calculations are based and which work rather well for molecules containing localized orbitals only, tend to fail when applied to highly delocalized systems such as Silylisothiocyanate. However the bond distances too indicate that there is a considerable amount of double bond character and thus d-orbital contribution in the region of the Si–N-bond.

For comparison we also have calculated the dipole moment by the semiempirical quantum mechanical CNDO/2 program using the original parametrization of Pople et al. $^{20}$ As input structure the $r_\alpha$-structure shown in Fig. 1 was used. The resulting dipole moment was $+0.8$ D (Si negative). This value includes a $+3.2$ D contribution due to p-d-orbital overlap in the Si–N-region. Although the calculated CNDO value falls about 1.6 D short of the observed value, we would assume the CNDO calculation as indicative to a dipole moment with Si at the negative end of the molecule. We plan to settle the question of the direction of $\mu_z$ experimentally by a separate investigation of the molecular rotational Zeeman effect of different isotopic species $^{21}$.

Better agreement was obtained between the experimentally determined quadrupole coupling constant and the value following from the CNDO-calculation. From a simplified MO treatment in which only the atomic orbitals centred at the nitrogen nucleus are assumed to contribute appreciably, the $^{14}$N quadrupole coupling constant follows as given in Eq. (6) $^{22}$:

$$\chi_{zz} = -\left(\frac{P_{p_x,p_z} + P_{p_y,p_z}}{2} - P_{p_z,p_z}\right)q_{210}(^{14}\text{N}) . \quad (6)$$

In Eq. (6) the value $-10$ MHz $^{23}$ was used for

$$q_{210}(^{14}\text{N}) = \left| e \langle \left| \frac{\nabla^2}{\nabla^2} \right| p_z \rangle \right| h .$$

$P_{p_x,p_z}$, $P_{p_y,p_z}$ and $P_{p_z,p_z}$ are the $p_x$, $p_y$ and $p_z$-densities at the $^{14}$N nucleus defined as:

$$P_{p_x,p_z} = 2 \sum_n |C_{p_x,n}|^2$$

etc. where $C_{p_x,n}$ is the coefficient of the $^{14}$N-$p_z$ atomic orbital in the n-th molecular orbital. With the CNDO-values $P_{p_x,p_z}^{\text{CNDO}} = 1.295$ and $P_{p_y,p_z}^{\text{CNDO}} = 1.225$ Eq. (6) predicts a $^{14}$N quadrupole coupling constant of $+0.70$ MHz which is in good agreement with the observed value of $+0.75$ MHz.

Fig. 5. Pauling electronegativities (in brackets) and ionic character (in %) of each covalent bond are given in the first row. The second row shows the resulting Pauling atomic charges, $Q_n$ (in units of $e$) for the two mesomer forms II and III. Also given are the corresponding electric dipole moments, calculated with the structure shown in Fig. 1 according to

$$\mu_n = \sum_n Q_n \cdot |e| \cdot z_n .$$

\[ \text{Fig. 5. Pauling electronegativities (in brackets) and ionic character (in %) of each covalent bond are given in the first row. The second row shows the resulting Pauling atomic charges, $Q_n$ (in units of $e$) for the two mesomer forms II and III. Also given are the corresponding electric dipole moments, calculated with the structure shown in Fig. 1 according to} \]
It is interesting to compare the $^{14}$N quadrupole coupling constant observed here with the one observed for the quasi-symmetric top SiH$_3$NCO ($\chi_{zz} = +1.8$ MHz$^{24}$). This comparison indicates, that the population of the nitrogen $p_x$ and $p_y$ orbitals is smaller for SiH$_3$NCS. The greater stability of the linear configuration in SiH$_3$NCS as compared to SiH$_3$NCO can thus be “explained” by a stronger delocalization of the $p_x$ and $p_y$ orbitals.

**Appendix:**

**The Stark Effect of the l-type Doublets**

For the discussion of the Stark-effect of the l-doubles we neglect all other vibrations except the degenerate $v_{10}$ bending motion. Within this simplified model the Eigenfunctions of the vibrational Hamiltonian which correspond to the l-type doublets may be approximated by the symmetrized products of a symmetric top Eigenfunction with an Eigenfunction of the two-dimensional harmonic oscillator$^{25}$ as given in Eq. (A.1):

$$\Psi_\pm(a, \beta, \gamma, r, \varphi, \zeta) = \frac{1}{\sqrt{2}} \left[ \Psi_{J,K=-1,M}(a, \beta, \gamma) + \Psi_{J,K=1,M}(a, \beta, \gamma) \right]$$

$$\Psi_{J,K,M}(a, \beta, \gamma) = \text{symmetric top Eigenfunction}$$

with $a, \beta, \gamma$ the Eulerian angles describing the orientation of the molecular coordinate system with respect to the space fixed Laboratory frame.

$$\Phi_{v,i}(r, \varphi) = \text{harmonic oscillator Eigenfunction}$$

with $r^2 = Q_{10x}^2 + Q_{10y}^2$ and $\tan \varphi = Q_{10y}/Q_{10x}$. $Q_{10x}$ and $Q_{10y}$ are the normal coordinates corresponding to the degenerate bending modes in x- and y-direction perpendicular to the molecular z-axis.

Within this basis, the 2 by 2 Hamiltonian submatrices corresponding to the $\Psi_+\text{-}$, $\Psi_-\text{-}$functions of Eq. (A.1) are diagonal, with a splitting of the diagonal elements given by $(q/4)(v + 1)J(J + 1)h^{26}$. In H$_3$SiNCS the “l-type doubling constant” $q$ has the value 2.783 MHz.

If the exterior Stark-field is switched on, the space degeneracy (M-degeneracy) is lifted due to the operator corresponding to the potential energy of the molecular electric dipole moment in the exterior field:

$$V_{\text{pot}} = -\mu \cdot E$$

$$= -\left[ (\mu_{0x} + \tilde{\mu}_r) Q_{10x}^2 + (\mu_{0y} + \tilde{\mu}_r) Q_{10y}^2 + \ldots \right] \cos z Z$$

$$+ (\mu_z Q_{10x} + \ldots) \cos x Z + (\mu_y Q_{10y} + \ldots) \cos y Z \right] E.$$
Here $\overline{W}_{J,|K|v}$ is the average energy of the $l$-doublet levels in the absence of the field. At low Stark-fields with $E$ only few V/cm one may neglect all other off diagonal Stark-effect matrix elements, since they connect widely spaced energy levels (typically on the order of several GHz).

Within this approximation the presence of the Stark-field leads to the following expressions for the energy levels, which are given by the Eigenvalues of the 2 by 2 matrices above:

$$W_+ = \overline{W}_{J,|K|v} + 1 + \left( \frac{q}{2} J(J+1) \right)^2 + \left( \langle |\mu| \rangle EM \right)^2,$$

$$W_- = \overline{W}_{J,|K|v} - 1 - \left( \frac{q}{2} J(J+1) \right)^2 + \left( \langle |\mu| \rangle EM \right)^2.$$  \hspace{1cm} (A.4)

Figure A.1 shows the corresponding field dependence of the $l$-doublet levels involved in the $J = 2 \rightarrow J' = 3, \ K = 1, \ l_{10} = 1, \ v_{10} = 1$ rotational transition of H$_3$SiNCS. Taking into account the microwave transition selection rules ($E_{\text{microwave}}$ parallel $E_{\text{Stark}}$) which follow from the dipole matrix elements within the basis given by Equations (A.1), the crossing of the Stark satellite frequencies with equal $|M|$ occurs at the frequency

$$v_0 = \left( \overline{W}_{J+1,|K|v} - \overline{W}_{J,|K|v} \right)/h$$

and the corresponding Stark field, $E_{c(M)}$ follows from the condition given in Eq. (A.5)

$$E_{c(M)} = \frac{h \left( \frac{q}{2} J(J+1) \right)^2 + \left( \langle |\mu_z| \rangle EM \right)^2}{J(J+1)(J+2)}.$$  \hspace{1cm} (A.5)

Due to the favourable $J$-dependence of the $q$- and $\langle |\mu_z| \rangle$-contributions, the square root may be drawn after rearranging. This leads to Eq. (A.6). With $E_{c(M)}$ the Stark-field at the crossing point:

$$q = \frac{\left( \frac{q}{2} J(J+1) \right)^2 + \left( \langle |\mu_z| \rangle EM \right)^2}{h J(J+1)(J+2)}.$$  \hspace{1cm} (A.6)

Since the zero field splitting between the $l$-doublet frequencies is given by $\Delta v_0 = 2q(J+1)$ (compare Fig. A.1) we may express $q$ in Eq. (A.6) by $\Delta v_0 = v_+ - v_-$ which leads to the final expression. Eq. (A.7) used to determine the expectation value $\langle \psi_{10} = 1, l = 1 | \mu_z | \psi_{10} = 1, l = 1 \rangle$ in the first excited state of the bending motion.

**Zero Field Energies**

$$W_{J=2}(\mu) = \left( J(J+1) \right)^2, \hspace{1cm} W_{J=1}(\mu) = \frac{J(J+1)}{2}.$$  \hspace{1cm} (A.1)

**Energies of Stark levels**

$$W_{J=2}(M) = \overline{W}_{J=2,k} \pm \frac{q}{2} J(J+1) \pm \left( \langle |\mu| \rangle EM \right)^2.$$  \hspace{1cm} (A.2)

**Limiting Wavefunctions at high Starkfields**

$$\lim_{\text{high } E} \psi_{J=2,\pm M} = \frac{\psi_{J=2,\pm M}}{\sqrt{2}}, \quad (\text{for } M = 1)$$

$$\lim_{\text{high } E} \psi_{J=3,\pm M} = \frac{\psi_{J=3,\pm M}}{\sqrt{2}}, \quad (\text{for } M = 2).$$

**Zero Field Wavefunctions**

$$\psi = \frac{1}{\sqrt{2}} \left( \psi_{\mu>0} + \psi_{\mu<0} \right)$$

$$\psi = \frac{1}{\sqrt{2}} \left( \psi_{\mu>0} - \psi_{\mu<0} \right).$$

Fig. A.1. To scale drawing of the field dependence of the $M_J$-sublevels for the $|K| = 1, \ J = 2 \rightarrow J' = 3$ $l$-doublet in H$_3$SiNCS. Also given are the energy expressions and wavefunctions for the limiting cases. (The electric dipole moment is assumed to point in the direction of the molecular axis.) $\overline{W}_{J,|K|v}$ stands for the average energy of the corresponding zero field doublet.
At higher Stark-fields such as used in the present work, the second order contributions, although still minor corrections, are no more negligible in the expressions for the energy levels. However they are practically identical for sublevels corresponding to the same $|M|$ values (equal matrix elements). Thus they drop out in the “crossing condition”, leaving the original expression Eq. (A.7) unaltered.

13. Ref. 4 b Equation (3).
17. Ref. 15 Appendix V.
19. Ref. 18, Sec. 7.
20. Ref. 5.
22. Ref. 15, Sec. 14.5.
25. For the symmetrical top wavefunctions and direction cosine matrix elements c.f. Ref. 11, Sec. 2.5 and Sec. 2.6. For the twodimensional harmonic oscillator c.f. L. Pauling and E. B. Wilson jr., Introduction to quantum mechanics, McGraw-Hill, New York 1935, Sec. IV-17.
26. For the definition of $q$ c.f. the review article on $t$-type doubling by T. Oka, J. Chem. Phys. 47, 5410 [1967].