High resolution GHz and THz (FTIR) spectroscopy and theory of parity violation and tunneling for 1,2-dithiine (C₄H₄S₂) as a candidate for measuring the parity violating energy difference between enantiomers of chiral molecules†

S. Albert, a,b I. Bolotova, a Z. Chen, a C. Fábri, a L. Horny, a M. Quack, *a G. Seyfang a and D. Zindel a

We report high resolution spectroscopic results of 1,2-dithiine- (1,2-dithia-3,5-cyclohexadiene, C₄H₄S₂) in the gigahertz and terahertz spectroscopic ranges and exploratory theoretical calculations of parity violation and tunneling processes in view of a possible experimental determination of the parity violating energy difference \( \Delta_{pv}E \) in this chiral molecule. Theory predicts that the parity violating energy difference between the enantiomers in their ground state (\( \langle \Delta_{pv}E \rangle \approx 11 \times 10^{-12} (hc) \text{ cm}^{-1} \)) is in principle measurable as it is much larger than the calculated tunneling splitting for the symmetrical potential \( \Delta E_s < 10^{-24} (hc) \text{ cm}^{-1} \). With a planar transition state for stereomutation at about 2500 cm\(^{-1}\) tunneling splitting becomes appreciable above 2300 cm\(^{-1}\). This makes levels of well-defined parity accessible to parity selection by the available powerful infrared lasers and thus useful for one of the existing experimental approaches towards molecular parity violation. The new GHz spectroscopy leads to greatly improved ground state rotational parameters for 1,2-dithiine. These are used as starting points for the first successful analyses of high resolution interferometric Fourier transform infrared (FTIR, THz) spectra of the fundamentals \( \nu_2 \) (1308.873 cm\(^{-1}\) or 39.23903 THz), \( \nu_2 \) (623.094 cm\(^{-1}\) or 18.67989 THz) and \( \nu_3 \) (544.900 cm\(^{-1}\) or 46.314937 THz) for which highly accurate spectroscopic parameters are reported. The results are discussed in relation to current efforts to measure \( \Delta_{pv}E \).

1 Introduction

According to the traditional point of view both in the framework of classical molecular structure \(^1\)\(^-\)\(^6\) and within the ordinary quantum theory of molecules retaining only the electromagnetic force \(^7\)\(^,\)\(^8\) the ground states of the enantiomers of chiral molecules are energetically exactly equivalent by symmetry. \(^1\)\(^-\)\(^5\)\(^,\)\(^10\) This would result in a reaction enthalpy \( \Delta_{re}H_0^\ominus \approx 0 \) exactly for the stereomutation reaction (1). However, the situation has fundamentally changed with the discovery of parity violation. \(^11\)\(^-\)\(^21\) In this case one predicts a small “parity violating” energy difference \( \Delta_{pv}E_0 \) between the ground states of the two enantiomers, leading to the prediction of a non-zero parity violating reaction enthalpy \( \Delta_{pv}H_0^\ominus \):

\[
P \rightarrow M \quad \Delta_{pv}H_0^\ominus = N_A \Delta_{pv}E_0
\]

(1)

where \( N_A \) is the Avogadro constant and we use the P and M notation for “axially chiral” molecules. This has important consequences for our understanding of the foundation of stereochemistry \(^10\) and possibly also of the evolution of biomolecular homochirality. \(^22\)\(^-\)\(^29\) There has been considerable theoretical work predicting the magnitude of \( \Delta_{pv}E \), first qualitatively \(^23\)\(^,\)\(^30\) then in semiquantitative computations \(^31\)\(^-\)\(^32\) all leading to exceedingly small absolute values. Recent progress in the theory of molecular parity violation, starting with our finding \(^33\) that the early estimates of \( \Delta_{pv}E \) were too low by up to two orders of magnitude for benchmark molecules such as H₂O₂ and related ones, confirmed by extensive subsequent work \(^34\)\(^-\)\(^46\) led to a new impetus to the field reviewed in ref. 9, 47 and 48, including serious attempts to detect parity violation in chiral molecules, so far unsuccessful, however. While several different experimental schemes concerning molecular parity violation have been proposed in the past \(^26\)\(^,\)\(^30\)\(^,\)\(^49\)\(^-\)\(^53\) (see also the reviews in ref. 9, 10, 29, 47 and 54-56), only two of these appear to be actively pursued at present, as outlined in Fig. 1. In this figure the solid lines represent measurable energy levels of the chiral molecule under consideration, whereas the dotted lines refer to the potential energy differences.
minima including the parity violating potential. In theory the measurable energy represented by the solid lines would be obtained from the expectation values of the multidimensional parity violating potential in the quantum state considered, added to the energy eigenvalues of that state as computed from parity conserving ordinary molecular quantum mechanics (see also Section 2).

In a first experimental scheme originally proposed by Letokhov and coworkers, one measures the difference in line positions, say, in the infrared spectrum of the separate enantiomers \((h\nu_M - h\nu_P)\). This introduces a difference \(\Delta_p E\) between the two parity violating energy differences \(\Delta_p E^*\) and \(\Delta_p E_0\) in two different energy levels. Early attempts towards such experiments were reported by Kompanets and coworkers and Arimondo, Glorieux and Oki (both unsuccessful). The work of Kompanets et al. on CHFClBr was further pursued by our group using high resolution microwave and infrared spectroscopy in molecular beams with detailed rovibrational analyses in order to identify suitable lines for detecting parity violation in these spectra. These results of our group were subsequently used to carry out experiments at very high resolution by the Paris group achieving about \(\Delta \nu/\nu \approx 10^{-13}\) relative uncertainty, compared to theoretical predictions of shifts of the order \(\Delta \nu/\nu \approx 10^{-16}\). Recent progress by two groups following this scheme currently can be seen from ref. 59 and 60. One can estimate that successful experiments of this kind might be possible in the near future for chiral molecules involving very heavy atoms which have relatively large values of \(\Delta_p E\) because of the well-known scaling with atomic number. Here it must be noted that atomic spectroscopy has already been successful to detect parity violation for very heavy atoms such as Cs, Bi etc., where a current limitation in the fundamental analysis actually results from uncertainties in the theory for such heavy-atom systems, which will be also a drawback if such experiments are successful on related molecules (see ref. 9 and 29 for a discussion). Another drawback of this first scheme is that it cannot provide \(\Delta_p E_0\) (or \(\Delta_p E^*\)) separately. Also, this scheme requires the synthesis of separate enantiomers. We shall not discuss this scheme further here.

In the second scheme, proposed in ref. 52, one uses an excited intermediate level of well-defined parity (marked \(E^*\) for positive parity in Fig. 1) which can be reached by electric dipole transitions from both enantiomers (marked \(h\nu_p\) and \(h\nu_M\) in Fig. 1). Then one can obtain \(\Delta_p E_0\) by a combination difference \((h\nu_p - h\nu_M)\). Alternatively, one can use a time dependent variant of this scheme whereby a sequence of two electric dipole transitions to a superposition state of the two enantiomers is prepared. This superposition state has a well-defined parity initially (say, with a probability \(|\psi(0)|^2 = 1\), which evolves in time according to eqn (2) for the complementary population of the state of positive parity detectable with high sensitivity on a “zero background”\(^{9,52}\).

\[
p\psi(t) = 1 - p\psi(t) = \sin^2(\pi \Delta_p E t / \hbar).
\]

Here, we use the notation \(\Delta_p E\) for some general quantum state which may be the ground state (then one has \(\Delta_p E = \Delta_p E_0\)), the excited state with \(\Delta_p E = \Delta_p E^*\) in Fig. 1, or some other selected quantum state. Recent detailed theoretical simulations have shown the feasibility of such experiments, in principle, for the realistic, simple chiral molecule ClOOCl. Further experimentation of principle has been demonstrated for the simple achiral molecule NH\(_3\), where the current experimental sensitivity indicates that parity violating energy differences on the order of about 100 aevor \((\hbar c)^{-1}\) J mol\(^{-1}\) should be detectable with the existing set up. Such values are predicted for chiral molecules with atoms no heavier than sulfur or chlorine which is a great advantage for a future theoretical analysis of experiments with very high accuracy in addition to the advantage of providing separate values for individual \(\Delta_p E\). Another advantage of the second scheme is that experiments can be carried out on racemic mixtures as well as on separate enantiomers.

We should note that a general condition for both experimental schemes is that the parity violating energy difference \(\Delta_p E\) is much larger than the tunneling splitting \(\Delta E_{\pm}\), calculated using the hypothetical symmetrical (parity conserving) Hamiltonian, thus

\[
|\Delta_p E| \gg |\Delta E_{\pm}|.
\]

Indeed, this condition is a necessary requirement for an energy level scheme as in Fig. 1 to be applicable at all. The inequality (3) does not hold for chiral molecules such as HOOH and HSSH but has been predicted theoretically to be fulfilled for ClOOCl and ClSSCl, for example, and also for the case of 1,2-dithiine to be studied here.

Current spectroscopic techniques result in some limitations on the complexity of the chiral molecules which can be studied. Also spectroscopically accessible states of well-defined parity must be identified by appropriate high resolution analyses. Such states can be found in electronically excited states, for instance, in molecules such as difluoroallene or they can be found in the electronic ground state at energies near or above the barrier for stereomutation as shown for ClOOCl. One can thus identify the following steps in preparing for experiments on \(\Delta_p E\) in chiral molecules.

1. Identify suitable chiral molecules by approximate exploratory theoretical calculations, demonstrating sufficiently large absolute
values $|\Delta \rho E|$ to be measurable and small absolute values $|\Delta E_s|$ for the tunneling splitting such that the inequality (3) holds.

(2) Carry out the necessary synthesis and exploratory high resolution spectroscopic analyses.

(3) Identify spectroscopic lines suitable to carry out the experiment according to the second scheme.

(4) Carry out the experiment to measure $\rho_i(t)$ according to eqn (2) with significant accuracy to provide $\Delta \rho E$.

(5) Analyse highly accurate experimental results of $\Delta \rho E$ by means of highly accurate theoretical calculations to extract fundamental parameters of the standard model of particle physics (SMPP) such as the Weinberg parameter which may be significantly different in experiments of high energy physics and “low energy atomic and molecular physics” spectroscopic experiments, for instance.

In the present work we show that the chiral molecule 1,2-dithiine is a possible candidate for experiments on $\Delta \rho E$ by carrying out in essence steps 1 and 2 of the program listed above. In Section 2 we show by theoretical calculations that 1,2-dithiine has a favourable, large absolute value $|\Delta \rho E|$ and a very small ground state tunneling splitting $|\Delta E_s|$ satisfying the inequality (3). Furthermore the barrier for stereomutation is calculated to be low enough for states above the barrier with well-defined parity to be accessible by the currently available high resolution lasers in the infrared range.

1,2-Dithiine as shown in Fig. 2 is a six membered chiral ring compound of $C_2$ symmetry which has been synthesized in ref. 77 and 78 and since this early synthesis combined with available high resolution lasers in the infrared range.70

The predicted ring structure possesses $C_2$ symmetry and the interesting non-planar structure of 1,2-dithiine is shown in Fig. 2 (C4H4S2) and principal axes together with the general atom numbering scheme (P enantiomer, sulfur yellow (1,2), carbon black (3,4,5,6) and hydrogen light grey (7,8,9,10)).

Fig. 2. Perspective drawing of the molecular structure of 1,2-dithiine (C4H4S2) and principal axes together with the general atom numbering scheme (P enantiomer, sulfur yellow (1,2), carbon black (3,4,5,6) and hydrogen light grey (7,8,9,10)).
Table 1. Optimized equilibrium structure parameters (\(r_a\), in pm, angles in degrees) of the ground electronic state \(X^1_A^1\) of 1,2-dithiine (C\(_2\)v symmetry, atom numbering as in Fig. 2). The MP2 calculations were done using the Gaussian 09 package, and the CCSD(T) calculations using the Molpro program package. (We indicate: method/basis set as shown)

<table>
<thead>
<tr>
<th>(r_a) (A)</th>
<th>MP2/cc-pVTZ</th>
<th>MP2/cc-pVQZ</th>
<th>MP2/cc-pV5Z</th>
<th>CCSD(T)/cc-pVTZ</th>
<th>Exp.(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(r(S_1C_6))</td>
<td>176.21</td>
<td>175.58</td>
<td>175.17</td>
<td>177.59</td>
<td>175.9(4)</td>
</tr>
<tr>
<td>(r(S_2S_3))</td>
<td>206.23</td>
<td>204.77</td>
<td>203.88</td>
<td>208.35</td>
<td>205.1(3)</td>
</tr>
<tr>
<td>(r(S_3C_6))</td>
<td>135.08</td>
<td>134.91</td>
<td>134.93</td>
<td>134.89</td>
<td>135.3(3)</td>
</tr>
<tr>
<td>(r(C_6C_5))</td>
<td>144.71</td>
<td>144.44</td>
<td>144.36</td>
<td>146.12</td>
<td>146.1(1)</td>
</tr>
<tr>
<td>(r(C_6H_7))</td>
<td>108.21</td>
<td>108.16</td>
<td>108.16</td>
<td>108.32</td>
<td>-</td>
</tr>
<tr>
<td>(r(C_5H_{10}))</td>
<td>108.25</td>
<td>108.19</td>
<td>108.17</td>
<td>108.41</td>
<td>-</td>
</tr>
<tr>
<td>(r(S_1S_2C_6))</td>
<td>97.99</td>
<td>98.12</td>
<td>98.19</td>
<td>98.27</td>
<td>98.7(2)</td>
</tr>
<tr>
<td>(r(S_1C_6C_5))</td>
<td>121.39</td>
<td>121.17</td>
<td>121.07</td>
<td>121.88</td>
<td>121.4(2)</td>
</tr>
<tr>
<td>(r(C_6C_5H_{10}))</td>
<td>124.18</td>
<td>124.14</td>
<td>124.07</td>
<td>124.40</td>
<td>124.2(2)</td>
</tr>
<tr>
<td>(r(C_6C_5H_7))</td>
<td>116.65</td>
<td>116.77</td>
<td>116.90</td>
<td>116.09</td>
<td>-</td>
</tr>
<tr>
<td>(r(C_6C_5H_{10}))</td>
<td>117.85</td>
<td>117.87</td>
<td>117.90</td>
<td>118.14</td>
<td>-</td>
</tr>
<tr>
<td>(r(C_5S_1S_2C_3))</td>
<td>54.99</td>
<td>55.31</td>
<td>55.59</td>
<td>53.25</td>
<td>53.9</td>
</tr>
<tr>
<td>(r(S_1S_2C_6H_7))</td>
<td>144.14</td>
<td>141.07</td>
<td>141.62</td>
<td>141.82</td>
<td>-</td>
</tr>
<tr>
<td>(r(S_1S_2C_6C_5))</td>
<td>52.27</td>
<td>52.37</td>
<td>52.51</td>
<td>41.11</td>
<td>-</td>
</tr>
<tr>
<td>(r(S_1C_6C_5H_{10}))</td>
<td>177.25</td>
<td>177.18</td>
<td>177.85</td>
<td>177.85</td>
<td>177.85</td>
</tr>
</tbody>
</table>

\(a\) Experimental structural parameters from ref. 75 (\(r_a\) structure).

“out-of-plane” bending mode, followed by the ring twisting fundamental \(v_{24}\) = 214 cm\(^{-1}\) and the CH “in-plane” bending fundamental \(v_{17}\) = 1303 cm\(^{-1}\) where “out-of-plane” and “in-plane” have obviously only approximate meaning for this non-planar molecule. Further intense absorptions arise from the CC stretching polyads and the CH stretching polyads.

The twisted structure with a dihedral angle \(\tau(C_6S_1S_2C_3)\) of 53.25 degrees gives rise to P and M enantiomorphism, with a

Table 2. Calculated harmonic wavenumbers \(\tilde{\omega}_i\) (in cm\(^{-1}\)), IR intensities (in \(\text{km mol}^{-1}\)), and anharmonic fundamentals \(\tilde{\nu}_i\) (in cm\(^{-1}\)) of 1,2-dithiine as calculated using the Gaussian 09 package.

<table>
<thead>
<tr>
<th>Mode Symmetry</th>
<th>(\tilde{\omega}_i) (MP2/cc-pVTZ)</th>
<th>(\tilde{\nu}_i) (MP2/cc-pVTZ)</th>
<th>Approximate description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 A</td>
<td>3226</td>
<td>3083</td>
<td>CH stretches</td>
</tr>
<tr>
<td>2 A</td>
<td>3204</td>
<td>3077</td>
<td>CH stretches</td>
</tr>
<tr>
<td>3 A</td>
<td>1568</td>
<td>1222</td>
<td>CC stretches</td>
</tr>
<tr>
<td>4 A</td>
<td>1390</td>
<td>1349</td>
<td>CH in-plane bends</td>
</tr>
<tr>
<td>5 A</td>
<td>1181</td>
<td>1164</td>
<td>CH in-plane bends</td>
</tr>
<tr>
<td>6 A</td>
<td>997</td>
<td>981</td>
<td>CH in-plane bends</td>
</tr>
<tr>
<td>7 A</td>
<td>938</td>
<td>920</td>
<td>CH out-of-plane bends</td>
</tr>
<tr>
<td>8 A</td>
<td>780</td>
<td>767</td>
<td>CH out-of-plane bends</td>
</tr>
<tr>
<td>9 A</td>
<td>740</td>
<td>728</td>
<td>CH out-of-plane bends</td>
</tr>
<tr>
<td>10 A</td>
<td>573</td>
<td>565</td>
<td>CH out-of-plane bends</td>
</tr>
<tr>
<td>11 A</td>
<td>523</td>
<td>516</td>
<td>CH out-of-plane bends</td>
</tr>
<tr>
<td>12 A</td>
<td>448</td>
<td>441</td>
<td>CH out-of-plane bends</td>
</tr>
<tr>
<td>13 A</td>
<td>204</td>
<td>200</td>
<td>Ringucker</td>
</tr>
<tr>
<td>14 B</td>
<td>3232</td>
<td>3115</td>
<td>CH stretches</td>
</tr>
<tr>
<td>15 B</td>
<td>3197</td>
<td>3075</td>
<td>CH stretches</td>
</tr>
<tr>
<td>16 B</td>
<td>1610</td>
<td>1563</td>
<td>CC stretches</td>
</tr>
<tr>
<td>17 B</td>
<td>1329</td>
<td>1303</td>
<td>CH in-plane bends</td>
</tr>
<tr>
<td>18 B</td>
<td>1184</td>
<td>1166</td>
<td>CH in-plane bends</td>
</tr>
<tr>
<td>19 B</td>
<td>929</td>
<td>910</td>
<td>CH out-of-plane bends</td>
</tr>
<tr>
<td>20 B</td>
<td>858</td>
<td>847</td>
<td>CH in-plane bends</td>
</tr>
<tr>
<td>21 B</td>
<td>702</td>
<td>684</td>
<td>CH asym. stretches</td>
</tr>
<tr>
<td>22 B</td>
<td>632</td>
<td>623</td>
<td>CH out-of-plane bends</td>
</tr>
<tr>
<td>23 B</td>
<td>315</td>
<td>312</td>
<td>CSS in-plane bends</td>
</tr>
<tr>
<td>24 B</td>
<td>214</td>
<td>214</td>
<td>CCC out-of-plane bends</td>
</tr>
</tbody>
</table>

planar structure of \(C_{2v}\) symmetry being the transition state for interconversion between the two enantiomers (Fig. 3 and Table 3). Formally, this corresponds to the cis-transition state of general disulfides with internal rotation. 71,72 The S–S bond length is elongated to 217.8 pm (CCSD(T)/cc-pVDZ level) and one finds as angles \(\angle(C_6S_1S_2C_3) = 104.43^\circ\) and \(\angle(S_1C_6C_5) = 129.72^\circ\) for the transition state which are the only structural parameters apart from the obvious dihedral angles differing substantially from the equilibrium structures. The transition state as calculated at the CCSD(T)/cc-pVQZ level of theory is found to be about 2500 cm\(^{-1}\) above the potential minimum (without vibrational zero-point energy correction). The planar structure is shown in Fig. 3 which also indicates the atom numbering with C\(_6\), S\(_1\), S\(_2\), C\(_3\), C\(_4\), C\(_5\) and H\(_7\), H\(_8\), H\(_9\), H\(_{10}\). The structural parameters are summarized in Table 3 and the harmonic wavenumbers of the transition state are given in Table 4 with the species in \(C_{2v}\) symmetry.

The parity-conserving electronic \((V_e)\) and parity-violating potentials \((E_{pv})\) computed along the IRC interconversion path are given in Fig. 4. \(E_{pv}\) was computed with our recently developed \(^{44,97}\) coupled-cluster singles and doubles linear response approach (CCSD-LR) using the Zurich version of the PSI3 program. \(^{98}\) \(E_{pv}\) is obtained as a linear response function of

Table 3. Optimized molecular structure parameters (\(r_a\), in pm, angles in degrees) of the planar transition state for the stereomutation of 1,2-dithiine (\(C_{2v}\) symmetry). The MP2 calculations were done using the Gaussian 09 package, and the CCSD(T) calculations using the Molpro program package. 74

| \(r(S_1C_6)\) | 175.36 | 174.81 | 177.97 |
| \(r(S_2S_3)\) | 212.78 | 211.46 | 217.82 |
| \(r(C_6C_5)\) | 134.18 | 133.95 | 135.75 |
| \(r(C_6H_7)\) | 145.37 | 145.18 | 147.54 |
| \(r(C_6H_{10})\) | 108.30 | 108.24 | 109.94 |
| \(r(C_5C_6)\) | 108.10 | 108.04 | 109.75 |
| \(r(S_1S_2S_3)\) | 104.73 | 104.88 | 104.43 |
| \(r(S_1C_6C_5)\) | 129.57 | 129.49 | 129.72 |
| \(r(S_1C_6H_7)\) | 125.70 | 125.63 | 125.85 |
| \(r(S_1C_6H_{10})\) | 116.67 | 116.71 | 117.01 |
the coupled cluster wavefunction with an effective one-electron spin–orbit coupling serving as a static perturbation. We employed a decontracted cc-pVDZ basis set augmented with a set of steep s and p functions. Details of the theoretical approach have been described in ref. 44.

Based on our calculations, and as can be seen from Fig. 4, we predict the P-enantiomer to be stabilized with respect to the M-enantiomer. The computed value of $E_{\text{pv}}$ for P-1,2-dithiine is $E_{\text{pv}}/(\hbar c) = -5.72 \times 10^{-12}$ cm$^{-1}$. The signed electronic parity violating the energy difference $\Delta_{\text{pv}}E(q)$ between the two enantiomers as defined by eqn (4) is obtained to be

$$\Delta_{\text{pv}}E(q) = E_{\text{pv}}(q)_{\text{P}} - E_{\text{pv}}(q)_{\text{M}} = (\hbar c) 11.44 \times 10^{-12} \text{ cm}^{-1} \quad (4)$$

Table 4 Calculated harmonic wavenumbers $\tilde{\omega}_i$ (in cm$^{-1}$) of the planar transition state for the stereomutation of 1,2-dithiine ($i = \sqrt{-1}$) as calculated using the Gaussian 09 program package.$^3$

<table>
<thead>
<tr>
<th>Mode</th>
<th>Symmetry</th>
<th>$\tilde{\omega}_i$ (MP2/cc-pVTZ)</th>
<th>$\tilde{\omega}_i$ (MP2/cc-pVQZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$A_1$</td>
<td>3233</td>
<td>3231</td>
</tr>
<tr>
<td>2</td>
<td>$A_1$</td>
<td>3202</td>
<td>3202</td>
</tr>
<tr>
<td>3</td>
<td>$A_1$</td>
<td>1628</td>
<td>1626</td>
</tr>
<tr>
<td>4</td>
<td>$A_1$</td>
<td>1403</td>
<td>1402</td>
</tr>
<tr>
<td>5</td>
<td>$A_1$</td>
<td>1209</td>
<td>1208</td>
</tr>
<tr>
<td>6</td>
<td>$A_1$</td>
<td>985</td>
<td>985</td>
</tr>
<tr>
<td>7</td>
<td>$A_1$</td>
<td>729</td>
<td>732</td>
</tr>
<tr>
<td>8</td>
<td>$A_1$</td>
<td>513</td>
<td>515</td>
</tr>
<tr>
<td>9</td>
<td>$A_1$</td>
<td>458</td>
<td>462</td>
</tr>
<tr>
<td>10</td>
<td>$A_1$</td>
<td>927</td>
<td>928</td>
</tr>
<tr>
<td>11</td>
<td>$A_2$</td>
<td>746</td>
<td>743</td>
</tr>
<tr>
<td>12</td>
<td>$A_2$</td>
<td>503</td>
<td>509</td>
</tr>
<tr>
<td>13</td>
<td>$A_2$</td>
<td>1162</td>
<td>1168</td>
</tr>
<tr>
<td>14</td>
<td>$B_1$</td>
<td>926</td>
<td>926</td>
</tr>
<tr>
<td>15</td>
<td>$B_1$</td>
<td>642</td>
<td>640</td>
</tr>
<tr>
<td>16</td>
<td>$B_1$</td>
<td>263</td>
<td>264</td>
</tr>
<tr>
<td>17</td>
<td>$B_2$</td>
<td>3222</td>
<td>3221</td>
</tr>
<tr>
<td>18</td>
<td>$B_2$</td>
<td>3198</td>
<td>3199</td>
</tr>
<tr>
<td>19</td>
<td>$B_2$</td>
<td>1645</td>
<td>1644</td>
</tr>
<tr>
<td>20</td>
<td>$B_2$</td>
<td>1341</td>
<td>1342</td>
</tr>
<tr>
<td>21</td>
<td>$B_2$</td>
<td>1213</td>
<td>1212</td>
</tr>
<tr>
<td>22</td>
<td>$B_2$</td>
<td>850</td>
<td>851</td>
</tr>
<tr>
<td>23</td>
<td>$B_2$</td>
<td>678</td>
<td>681</td>
</tr>
<tr>
<td>24</td>
<td>$B_2$</td>
<td>314</td>
<td>315</td>
</tr>
</tbody>
</table>

where $q$ stands for the reaction coordinate along the IRC path. The value for $\Delta_{\text{pv}}E(q)$ is remarkably large and is related to the parity violating potential having its maximum as a function of the dihedral angle near the equilibrium geometry. It can be compared with the very similar values in the range $(11 \pm 1) \times 10^{-12}$ cm$^{-1}$ obtained with several methods in ref. 83.

In order to estimate the ground-state tunneling splitting $(\Delta E_{q})$ the $\tau(S_1\cdots S_2\cdots S_3)$ dihedral angle (denoted by $\tau$) was selected to be the reaction coordinate describing the interconversion of the two puckered enantiomers through a planar transition state. For every energy value as a function of $\tau$ the remaining internal coordinates were optimized at the MP2/cc-pVTZ level of theory and the resulting structures were then used for single-point CCSD(T)/cc-pVQZ electronic structure computations. This definition of the reaction coordinate was justified by MP2/cc-pVTZ IRC computations, where the resulting IRC path connecting the planar transition state with the two enantiomeric potential minima was found to be almost identical to the 1D MP2/cc-pVTZ reaction path following simply a variation of $\tau$. The structural parameters as a function of the reaction coordinate values $q_i$ and the harmonic wavenumbers as a function of $q$ are given in the ESL.$^\dagger$

We employed the quasi-adiabatic channel reaction path Hamiltonian approach (RPH)$^{99–101}$ to compute the tunneling splittings $\Delta E_{q}$. In conjunction with the Born–Oppenheimer potential (CCSD(T)/cc-pVQZ, see the dashed line in Fig. 5) we used Cartesian coordinates, energy gradients and harmonic force fields (all of these quantities were obtained at the MP2/cc-pVTZ level of theory) along the reaction path to generate the lowest quasi-adiabatic channel potential (Fig. 5, solid line). The barrier heights are 2529 cm$^{-1}$ (Born–Oppenheimer potential) and 2559 cm$^{-1}$ (lowest quasi-adiabatic channel potential). The RPH energy levels corresponding to the lowest quasi-adiabatic channel potential are given in Table 5. It can be seen from Table 5 that the tunneling splittings increase as the energy

![Fig. 4 Parity-violating potential $E_{\text{pv}}$ (CCSD-LR/cc-pVDZ) and the parity-conserving potential $V_q$ (CCSD(T)/cc-pVTZ) computed along the IRC interconversion path for 1,2-dithiine. The P enantiomer has negative values of $-\tau$, the M enantiomer has positive values of $-\tau$ (in degrees$^\circ$).](image1)

![Fig. 5 Potential energy function corresponding to the 1D reaction path (see the text for discussion). The electronic Born–Oppenheimer (dashed line) and the lowest quasi-adiabatic channel potentials (solid line) are referred to their respective minima being separated by the 23D zero point energy (h$\nu$) 14 882 cm$^{-1}$ and $t_{\text{CSSC}}$ denotes the $C_6$–$S_1$–$S_2$–$C_3$ dihedral angle. Using the shift by this large difference in reference energies, the two effective potentials almost coincide.](image2)
levels approach the barrier. At \( v = 12 \), about 2170 cm\(^{-1}\) above the minimum of the channel and still almost 400 cm\(^{-1}\) below the barrier the tunneling splitting of 0.1 cm\(^{-1}\) would be easily measurable in the infrared region. This large value is quite remarkable in view of the essentially pure “heavy atom” motion for the tunneling process.

Since the tunneling splittings of the lowest tunneling doublets are very small owing to the high interconversion barrier and large effective tunneling mass, their direct variational computation is not easily possible due to numerical limitations. In order to estimate \( \Delta E \) we invoked an extrapolation technique that has been successfully used for the calculation of small tunneling splittings in CISCI.\(^{21}\) This method resulted in a ground-state tunneling splitting of \( \Delta E_{\text{vs}}/h \approx 4 \times 10^{-5} \) cm\(^{-1}\). We have also calculated the expectation value of \( \Delta_{\text{pv}}E \) in the torsional ground state and found it to differ by less than 10% from \( \Delta_{\text{pv}}E \). Thus the parity violating energy difference \( \Delta_{\text{pv}}E \) clearly exceeds the tunneling splittings for the hypothetical symmetrical potential by many orders of magnitude and 1,2-dithiine is a suitable candidate for measuring \( \Delta_{\text{pv}}E \) by the technique proposed in ref. 52 from this point of view. We shall discuss further spectroscopic aspects in the following sections.

### 3 Experimental

#### 3.1 Synthesis of 1,2-dithiine

1,2-Dithiine was synthesized according to the scheme in Fig. 6 using a procedure which is a modification of ref. 81, as described here, because the original procedure from ref. 81, which was tried as well, did not give quite satisfactory results in step c.

\[ \text{1,4-Bis(trimethylsilyl)buta-1,3-diyne (2).} \]

\[ \text{1,4-Bis(benzylthio)buta-1,3-diyne (3).} \]

\[ \text{1,4-Bis(acetylthio)buta-1,3-diyne (4).} \]

\[ \text{1,2-Dithiine (5).} \]

\[ \text{Scheme for the synthesis of 1,2-dithiine.} \]

The reaction mixture was stirred at 78°C and 10 mbar. The yield was 78% and the purity was determined by GC-MS 77 to be 90%.

With a mechanical stirrer, a dry ice cooler, a funnel for solids and a 3-way valve (connection to a balloon, the apparatus and a tube to the fume hood) and slowly condensate 300 ml of ammonia at \(-78 \) °C into the reaction flask. After adding 4.1 g (186 mmol) of freshly cut sodium the colour turned to dark blue and the reaction mixture was stirred for 48 h. In liquid ammonia with sodium and ammoniumchloride at \(-78 \) °C.

Potassium hydroxide in methanol at \(-78 \) °C and iodine in Methanol at \(-78 \) °C. The red oil was then removed at 78°C and 10 mbar. The yield was 78% and the purity was determined by GC-MS to be 90%.

#### 3.2 1,2-Dithiine (5)

1,2-Dithiine (5) could be obtained according to the procedure of ref. 82. Only the workup differs from the method described therein. After extraction the solvent was removed at \(-78 \) °C and 10 mbar. The red oil was then condensed in a trap cooled with liquid nitrogen to give the expected 1,2-dithiine. This product was used without further purification. The substance is light sensitive. The yield was 55%
and the purity as determined by GC-MS was about 95%. Due to photochemical and further reactions impurities develop over time in the samples used for the spectroscopy. In particular, thiophene was observed by infrared spectroscopy. However, in the high resolution spectra the identity of the lines assigned to 1,2-dithiine was obvious from the spectra, also confirming the identity of the main substance.

3.2 GHz measurements of 1,2-dithiine

The ground state pure rotational spectra of 1,2-dithiine have been recorded between 65 and 117 GHz using our GHz spectrometer described in detail in ref. 103 and only slightly modified here. It consists of an Agilent synthesizer (E8257D PSG, Agilent Technologies Option 520 UNX) working in the range 250 kHz to 20 GHz with a frequency resolution of 0.001 Hz and frequency locked to a 10 MHz-rubidium standard (FS725, Stanford Research Systems) for short-term stability and to a GPS standard (TM-4, Spectrum Instruments Inc.) for long-term stability. The signal is frequency multiplied by a factor of 6 (S10MS-AG, OML Inc.) and coupled out to free space via a conical W-band antenna (QHW-WCRR, QuinStar Technology Inc.) leading to an operation in the frequency range of 67 to 118 GHz. The beam is focused through Teflon lenses into a 2.5 m path length glass cell equipped with two Teflon windows and mounted in a Brewster angle to the incoming and outgoing beam. Finally the beam is detected with a two-channel indium antimonide (InSb) bolometer [QFI/2(2),QMC Instruments Ltd.] after passing through a second Teflon lens. All transitions were measured using the frequency modulation technique (second harmonic lock-in detection) with a modulation frequency of 50 kHz.

The gas sample was prepared by introducing the vapour at a pressure of approximately 0.025 mbar (measured using two Baratron gauges 627B.1T and 627B11M, MKS Instruments) from a liquid sample to the 2.5 m glass cell, which was covered by an aluminum foil to prevent 1,2-dithiine from photochemical decomposition due to exposure to daylight. A typical measured linewidth (full-width-at-half-maximum) at 100 GHz was close to 200 kHz. Fig. 7 shows a survey spectrum in the GHz range.

3.3 FTIR measurements of 1,2-dithiine

The FTIR spectrum of 1,2-dithiine has been recorded using our Fourier transform spectrometer Bruker IFS 125 HR Zürich prototype (ZP 2001) in the region 600–3200 cm\(^{-1}\). The Zurich FTIR setup is described in detail in ref. 106–109. The effective resolution ranged from 0.001 cm\(^{-1}\) in the range 600–1000 cm\(^{-1}\), close to the Doppler width (FWHM), which ranged from 0.0006 cm\(^{-1}\) at 300 cm\(^{-1}\) to 0.0036 cm\(^{-1}\) at 3000 cm\(^{-1}\). A White-type cell with path lengths ranging from 3.2 m up to 19.2 m and a 3 m glass cell were used for room temperature (295 K) measurements. The sample pressure measured using a MKS Baratron was varied between 0.1 and 1 mbar. All spectra were self-apodized. Table 6 shows the measurement parameters. Apertures from 0.8 mm to 1.0 mm were used. The spectra were calibrated with OCS (600–1300 cm\(^{-1}\))\(^{104,109}\) and water (1280–1365 cm\(^{-1}\))\(^{105}\). In general, the calibrated wavenumbers are estimated to be accurate within 0.0002 cm\(^{-1}\). The resolutions specified in Table 6 correspond to nominal bandwidths defined as 0.9 × 1/\text{dMOPD}\(^{109}\). The data given in the ESI† correspond to calibrated wavenumbers. Due to the instability of 1,2-dithiine some impurities arising from reaction products such as thiophene have been identified in the spectra. As a survey we also measured further spectra covering the range 800–5000 cm\(^{-1}\) at low resolution.

4 Rotational and rovibrational assignments

4.1 General aspects and symmetry considerations

Table 7 includes the character tables for the point group C\(_2\), the molecular symmetry groups \(M_{S_2}\) and \(M_{S_4}\) including the possibility of tunneling following Longuet-Higgins\(^{114}\) and the systematic notation of ref. 110 for the symmetry species indicating parity explicitly by + and −. We also show in Table 7 the notation for the \(C_{4v}\) symmetry group of the transition state and the induced
representations $\Gamma(M_b)\uparrow\Gamma(M_a)$ which indicate the symmetries of the tunneling sublevels. The nuclear spin statistical weights $g$ arising from the $2^4 = 16$ nuclear spin functions of the 4 protons ($H_2$, $H_4$, $H_8$, $H_{10}$) combined with the motional functions to Pauli allowed states are indicated for each symmetry. The combination of the rotational quantum numbers $K_a$ and $K_c$ for the asymmetric top in a totally symmetric vibronic level is given as well in Table 7, which also includes the number of vibrational modes of each symmetry ($n_{fv}$). According to the $C_2$ symmetry the modes with A symmetry generate $a$-type transitions and the modes with B symmetry generate $b$- and $c$-type transitions.

In a more detailed description the modes with A symmetry can split into $A_2$ and $A'$ symmetry and the modes with B symmetry into $B_1$ and $B_2$ symmetry in the planar transition state as shown in Tables 2 and 4. As a consequence the fundamentals with B symmetry generate mainly $c$-type transitions and weak $b$-type transitions if they correspond to out-of-plane modes in the planar transition state ($B_2$) or stronger $b$-type transitions than $c$-type transitions if they correspond to in-plane modes ($B_1$) in the planar transition state.

We have also calculated the electric dipole transition moment components $\mu_a$, $\mu_b$, and $\mu_c$ for the vibrational fundamentals in order to assist the assignments. The fundamentals with A symmetry generate weak $a$-type transitions if the modes correspond to out-of-plane modes ($A_2$) in the planar transition state because modes with $A_2$ symmetry are not infrared active. This is important with respect to the ring puckering mode $\nu_{13}$ which would correspond to an $A_2$ mode in the planar configuration. For that reason the fundamental $\nu_{13}$ is extremely weak. However, fundamentals with A symmetry generate strong $a$-type transitions if they correspond to in-plane modes in the planar transition state.

### 4.2 Assignment procedure

Fig. 7 shows part of the ground state rotational spectrum of 1,2-dithiine in the range 97–102.5 GHz. The assignment of the rotational transitions has been performed using the Pgopher program,\(^{115,116}\) a Loomis–Wood assignment program, and the WANG program\(^{117}\) up to $J = 50$. The infrared spectral region between 600 cm\(^{-1}\) and 1000 cm\(^{-1}\) as illustrated in Fig. 8 shows one strong absorption feature, and the region between 1150 cm\(^{-1}\) and 2200 cm\(^{-1}\) shows two strong absorption bands of 1,2-dithiine at 1310 cm\(^{-1}\) and 1590 cm\(^{-1}\). The strong sharp lines visible in Fig. 8 are due to water absorption lines. In the following description the term ‘subband’ or ‘series’ describes the transitions belonging to one $K_a$ or $K_c$ value. The assignment of the observed rovibrational transitions belonging to a particular subband consisting of $P$ and $R$ branches has been carried out efficiently using an interactive Loomis–Wood (LW) assignment program\(^{118}\) (see also ref. 109 and 119) previously designed for linear molecules.\(^{120–122}\) This limitation is, however, only superficial as the assignment program has been used successfully for several asymmetric top molecules: CHClF\(_2\),\(^{123,124}\) CHClF\(_3\),\(^{108,125}\) CDBrClF\(_3\),\(^{106}\) pyridine, and pyrimidine.\(^{126}\)

### 4.3 Ground state of 1,2-dithiine

1,2-Dithiine is an asymmetric rotor with $C_2$ symmetry, its only permanent electric dipole moment component lies along the

---

**Table 7** Character table for the $C_2$ and $M_2\$ symmetry groups (upper table) and character table for the $C_{2v}$ and $S_{2v}(C_{2v})$ symmetry groups (lower table). For the molecular symmetry group ($M_2\$) $(\alpha\beta)$ corresponds to the combined permutation of the symmetrically equivalent nuclei of the molecule and the upper right index of the symmetry species indicates parity (+ or −).\(^{110–113}\)

$$
\begin{array}{cccccccc}
\text{C}_2 & \text{M}_2\$ & \text{E} & \text{C}_2 & \mu & J & K_aK_c & n_{fv} & n_{fs} & g \\
\hline
A & A & 1 & 1 & \mu_a & J_a & ee, eo & 13 & 10 & 10 & A' + A \\
B & B & 1 & -1 & \mu_c & J_c & oo, oe & 11 & 6 & 6 & B' + B' \\
\end{array}
$$

$$
\begin{array}{cccccccc}
\text{C}_{2v} & \text{S}_{2v}(\text{M}_2\$) & \text{E} & \text{C}_2 & \sigma_{zz} & \sigma_{xy} & \sigma_{yy} & \mu & J & K_aK_c & n_{fv} & n_{fs} & g \\
\hline
A_1 & A' & 1 & 1 & 1 & 1 & \mu_a & ee & 9 & 10 & 10 \\
A_2 & A' & 1 & 1 & -1 & -1 & \mu_a & J_a & eo & 4 & 0 & 10 \\
B_1 & B' & 1 & -1 & 1 & -1 & \mu_c & J_c & oo & 3 & 0 & 6 \\
B_2 & B' & 1 & -1 & -1 & 1 & \mu_c & J_c & oe & 8 & 6 & 6 \\
\end{array}
$$
a-axis ($\mu_a = 1.85$ D\textsuperscript{75}), allowing transitions obeying $a$-type selection rules (ee ↔ ee and oe ↔ oo) for rotational transitions. The assignment of the rotational transitions observed here was assisted by using previously reported spectroscopic parameters from Gillies et al.\textsuperscript{75} which included only 15 transitions up to $J = 5$, $K_a = 5$. A total of 560 transitions were newly assigned up to $J \leq 50$ and $K_a \leq 19$ in the range of 65 to 117 GHz in the present work. The overview spectrum in Fig. 7 illustrates the rotational structure of 1,2-dithiine in the ground state such as the stronger $^R$-type transitions progressing nicely with separations between adjacent $K_a$ lines by about 600 MHz, while the $^Q$-type transitions are overshadowed and clustered.

### 4.4 The $\nu_{22}$ band of 1,2-dithiine

The $\nu_{22}$ band of 1,2-dithiine at 623 cm\textsuperscript{-1} (Fig. 8) is the strongest band in the IR absorption spectrum of 1,2-dithiine and consists of $c$- and $b$-type transitions. A comparison with the FTIR spectra of the already analysed aromatic molecules naphthalene\textsuperscript{127} azulene\textsuperscript{128} and phenol\textsuperscript{129} illustrates that the $\nu_{22}$ fundamental of 1,2-dithiine corresponds to the strongest out-of-plane fundamentals of these aromatic molecules which are also dominated by strong Q branches due to $c$-type transitions. However, the planar aromatic molecules show no $b$-type transitions according to the $C_{2v}$ symmetry. The $c$- and $b$-type transitions are not split until $K_a < 11$. The $c$-type series were identified as $P$, $R$ and $Q$ branches with ee ↔ oe and eo ↔ oo transitions. In addition, some $b$-type lines (around 20) above $K_a \geq 11$ have been assigned with ee ↔ oo and eo ↔ oe transitions. The spacing between two transitions of a $c$-type series is approximately 2A.

The assignments were checked by comparison with ground state combination differences. Loomis–Wood diagrams of this band are shown in Fig. 9. The patterns of $P$ and $R$ branches of the $c$-type series are clearly visible in Fig. 9. The upper diagram shows the $P$ branch and the middle diagram the $R$ branch. The visible series are transitions where $c$- and $b$-types fall together. The lines have been assigned up to $J \leq 78$ and $K_a \leq 73$ and $K_c \leq 34$.

### 4.5 The $\nu_{17}$ band of 1,2-dithiine

The observed spectrum of the $\nu_{17}$ fundamental of 1,2-dithiine at 1308 cm\textsuperscript{-1} clearly shows a characteristic $b$-type contour within the $P$ and $R$ branches and a $c$-type contour within the sharp center $Q$ branch as shown in Fig. 8 (middle panel) and in more detail in Fig. 13. The shape of the $b$-type series is very similar to the shape of the $b$-type series assigned in the $\nu_{15}$ fundamental of fluorobenzene.\textsuperscript{130} However, due to the $C_{2v}$ symmetry of fluorobenzene the $\nu_{15}$ fundamental shows no $c$-type transition and therefore no visible $Q$ branch. The $\nu_{17}$ band was chosen to be analyzed first, as a series of regularly spaced spectral patterns can be identified even through preliminary visual inspection. A simulated spectrum was generated using the estimated band center from inspecting the recorded high resolution data and the ground state spectroscopic parameters obtained from the analysis of the rotational spectra measured in the present work. The first attempt to assign the observed spectrum was based on the comparison with this simulated spectrum. The preliminarily assignments of the transitions were then confirmed by comparing the ground state combination differences with the GHz data. The simulated spectrum was refined by newly added assigned transitions and this process was continued in an iterative fashion until a few progressions of transitions were assigned. However, as the Loomis–Wood diagram of the $P$ branch in Fig. 9 (lower part) illustrates, the $b$-type subbands are perturbed from $J = 32$ and onwards and therefore have only been assigned up to $J \leq 32$. A closer look at the Loomis–Wood diagram indicates that the $\nu_{17}$ state is perturbed from at least two states: one with higher energy and smaller rotational $C$ constant and the second with lower energy and larger rotational $C$ constant. Only $b$-type transitions were assigned. The $c$-type transitions are not rotationally resolved in this band.
4.6 The $\nu_3$ band of 1,2-dithiine

The $\nu_3$ band centered at 1544.9 cm$^{-1}$ exhibits a strong absorption feature in the recorded spectrum as shown in the FTIR survey spectrum in Fig. 8 (middle trace). The strong sharp lines are due to water absorption. The assignment as the $\nu_3$ fundamental is consistent with the predicted intensity of this band being the highest in the region of 1400–1600 cm$^{-1}$ (Table 2). A few strong $a$-type transitions with low $K_a$ values were readily assigned with the aid of Loomis–Wood diagrams and simulated spectra using ground state constants and the estimated band center allowed a better prediction of more transitions to be assigned. As for the $\nu_{27}$ band, local perturbations were encountered and the assignment of lines was carried out up to $J = 40$ only. Also, the relatively noisy background prevented the transitions with $K_a$ larger than 10 from being assigned.

5 Results of the spectroscopic parameters and discussion

The rovibrational analysis has been carried out using Watson’s $A$ reduced effective Hamiltonians in the $I^r$ representation (with the definitions of axes according to Fig. 2) up to sextic centrifugal distortion constants:\textsuperscript{117,132}

$$\hat{H}_{\text{rot}}^{\text{v,v}} = A_v \hat{J}_z^2 + B_v \hat{J}_y^2 + C_v \hat{J}_z^2 - A_k \hat{J}_x^2 - A_{\kappa k} \hat{J}_x^2 - A_{\kappa z} \hat{J}_z^2 - \frac{1}{2} (\delta_{jk} J_j^2 + \delta_{kj} J_j^2) (J_x^2 + J_z^2) + \phi_j (J_j^2)^2 + \phi_{jk} J_j^2 J_j^2 + \phi_{kj} J_j^2 J_j^2 + \phi_{kJ} J_j^2 J_j^2 + \phi_{\kappa j} J_j^2 + \phi_{\kappa k} J_j^2 + \phi_{\kappa z} J_j^2 J_j^2 + \phi_{\kappa z} J_j^2 J_j^2 + \phi_{\kappa z} J_j^2 J_j^2 + (J_x^2 + J_z^2)^2)$$

The angular momentum operators are given by $\hat{J}_x = \hat{J}_x^2 + \hat{J}_y^2 + \hat{J}_z^2$ and $J_\pm = \hat{J}_x \pm i \hat{J}_y$. The $I^r$ representation was chosen to reduce correlations during the fit. The spectroscopic data were analyzed using the WANG program described in detail in ref. 117 and the SPFIT program.\textsuperscript{132} The spectroscopic constants were fitted for each band separately according to the $A$-reduction.

5.1 Rotational analysis and parameters of the ground state of 1,2-dithiine

560 rotational transitions in the GHz region were combined with the 15 lines reported in ref. 75 in a joint least squares analysis. Using only the three rotational constants and five centrifugal distortion constants included in the adjustment, the overall $d_{\text{rms}}$ of the fit consisting of 575 rotational transitions is remarkably low (less than 7 kHz, or 0.0000002 cm$^{-1}$). Table 8 lists all the spectroscopic parameters of the ground state of 1,2-dithiine. The rotational constants $A$, $B$ and $C$ obtained here compare well with those determined in the earlier microwave work. However, the previous study did not have a sufficient number of transitions (just a total of 15 lines) to accurately determine centrifugal distortion constants. In our work we observed more than 500 transitions and also covered a large range of the rotational spectrum with quantum numbers extending to $J \leq 50$ and $K_a \leq 19$, which led to a significant improvement in these centrifugal distortion constants. It was possible to observe intensity alternation in the spectra due to the nuclear spin statistical weights. According to Table 7 the expected intensity alternation in the rotationally resolved spectra of 1,2-dithiine is $ee : eo : oo : oe = 10 : 10 : 6 : 6$. Fig. 10 shows as an example a comparison of the strong R branch lines (upper trace) with simulations using the spectroscopic constants from Table 8 and using nuclear spin statistical weights (middle trace) and simulations without these weights (lower trace). The lower panel displays an enlarged part of the upper panel. Even for congested lines the effects of nuclear spin statistical weights are visible, confirming the assignments. This complete set of ground state rotational parameters (Table 8) plays an important role in the subsequent analysis of the dense rovibrational spectra in the preliminary assignment stage, especially when the upper state is perturbed.

5.2 Rovibrational analysis and parameters of the $\nu_{22}$ band of 1,2-dithiine

According to the calculated transition moments $\mu_b = -1.33 \times 10^{-6}$ D and $\mu_c = -2.20 \times 10^{-3}$ D the $b$-type absorption lines are predicted to have less than 40% of the strength of the corresponding $c$-type transitions. Around 1500 $b$-type transitions and around 4000 $c$-type transitions have been used in the adjustment. However, most of these $b$-type transitions, as already mentioned, are from non-split $c$-type and $b$-type transitions for $K_c < 11$ (around 1480 lines). Pure $b$-type transitions (around 20)

| $A_v$/cm$^{-1}$ | 0.111061 | 0.111554\textsuperscript{a} |
| $B_v$/cm$^{-1}$ | 0.103524 | 0.103980\textsuperscript{a} |
| $C_v$/cm$^{-1}$ | 0.058925 | 0.058852\textsuperscript{a} |

\textsuperscript{a} Equilibrium rotational constants ($A_v$, $B_v$, $C_v$) from vibrational perturbation theory (t.w.) and experimental ground state rotational constants ($A_o$, $B_o$, $C_o$) from our present GHz and FTIR experiments. (t.w.) (‘semi-experimental’ values). \textsuperscript{b} This work including the lines of ref. 75.
Fitted fundamental (upper trace) and simulation of the measured R branch lines (lower trace). A complete simulation (upper trace) and a simulation with fixed nuclear spin statistical weights (lower trace). The lower panel of Fig. 11 is an enlarged region of the measured R branch lines. As one can see in the third panel there is a remarkably good agreement between the simulation and the experimental spectrum. The agreement between the measured and the simulated spectra is of comparable quality in both cases. Differences are due to numerous hot band lines not shown in the simulation and the relatively high noise level in the experiment.

Only 20% of the molecules are in the ground state at 295 K, while 80% molecules generate hot bands. The Q branch region in Fig. 12 illustrates numerous hot bands. The determination of the band center is only possible through the use of a Loomis–Wood assignment program. The lower two panels display an enlargement of the Q branch region. As one can see in the third panel there is a remarkably good agreement between the simulation and the experimental spectrum, considering the important hot band contributions. A partial rovibrational analysis was possible for one of the hot bands.

### 5.3 Rovibrational analysis and parameters of the $\nu_{17}$ band of 1,2-dithiine

As the $ab$ initio calculations shown in Table 2 suggest, the $\nu_{17}$ band is of B symmetry which permits both $b$- and $c$-type transitions with an intensity ratio of approximately 8:1 according to the calculations. A total of 1006 transitions obeying $b$-type selection rules (ee–ee and ee–oo) were assigned and analysed in a least squares adjustment varying only the three rotational constants and five centrifugal distortion constants of $\nu_{17}$ with a $d_{\text{rms}}$ = 0.00014 cm$^{-1}$ but fixing the parameters for $A_{\text{cs}}$, $\delta_b$, and $\delta_c$ to the ground state values. Although perturbations have been encountered from $J = 32$ onwards, there is shown in Fig. 11 and 12 for the R and Q branch regions. The upper panel of Fig. 11 shows the complete $\nu_{22}$ fundamental (upper trace) and a simulation (lower trace). The lower panel of Fig. 11 is an enlarged region of the measured R branch lines (upper trace). The lower traces show simulations with and without nuclear spin statistical weights. As the simulation illustrates the intensity effect due to nuclear spin statistical weights is not visible in this part of the spectrum. The agreement between the measured and the simulated spectra is of comparable quality in both cases. Differences are due to numerous hot band lines not shown in the simulation and the relatively high noise level in the experiment.

### Table 9 Spectroscopic constants in cm$^{-1}$ of the vibrational states $\nu_{17}$, $\nu_{22}$ and $\nu_3$ of dithiine in the A-reduction. If there are no uncertainties listed (in parentheses in terms of 1σ in units of the last digits), the parameter was fixed during the fit at the value indicated

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{\text{cs}}$</td>
<td>0.11010980 (1)</td>
</tr>
<tr>
<td>$B_{\text{cs}}$</td>
<td>0.1033660 (24)</td>
</tr>
<tr>
<td>$C_{\text{cs}}$</td>
<td>0.05857310 (19)</td>
</tr>
<tr>
<td>$\Delta A_{\text{e}}/10^{-6}$</td>
<td>0.000690 (20)</td>
</tr>
<tr>
<td>$\Delta B_{\text{e}}/10^{-6}$</td>
<td>0.001400 (92)</td>
</tr>
<tr>
<td>$\Delta C_{\text{e}}/10^{-6}$</td>
<td>-0.0005986</td>
</tr>
<tr>
<td>$\Phi_{\text{e}}/10^{-12}$</td>
<td>-1.181 (14)</td>
</tr>
<tr>
<td>$\Phi_{\text{e}}/10^{-12}$</td>
<td>1.410 (44)</td>
</tr>
<tr>
<td>$\Phi_{\text{e}}/10^{-12}$</td>
<td>-0.492 (30)</td>
</tr>
<tr>
<td>$\Phi_{\text{e}}/10^{-12}$</td>
<td>-0.4683 (57)</td>
</tr>
<tr>
<td>$\Phi_{\text{e}}/10^{-12}$</td>
<td>0.218 (15)</td>
</tr>
<tr>
<td>$\Phi_{\text{e}}/10^{-12}$</td>
<td>-0.421 (19)</td>
</tr>
<tr>
<td>$N$</td>
<td>1006</td>
</tr>
<tr>
<td>$d_{\text{rms}}$</td>
<td>0.00026</td>
</tr>
<tr>
<td>$I_{\text{max}}$</td>
<td>40</td>
</tr>
<tr>
<td>$K_{\text{max}}$</td>
<td>10</td>
</tr>
<tr>
<td>$K_{\text{max}}$</td>
<td>40</td>
</tr>
</tbody>
</table>
good agreement between the simulated spectrum based on the parameters shown in Table 9 and the observed spectra as shown in Fig. 13. Only unperturbed lines up to $J \leq 32$ have been used in the least squares adjustment. However, the assignment of the perturbed lines above $J > 32$ has been checked by ground state combination differences calculated from the perturbed P and R branch lines of $\nu_{17}$.

The strong Q branch as shown in Fig. 13 with a calculated $|\mu_4/\mu_2| = 2.8$ is due to c-type transitions according to the prediction. However, the Q branch region is more complicated due to numerous hot bands. It was not possible to identify single c-type transitions because of the strong congestion of lines which is in agreement with the predicted transitions. Some of the hot band lines can be grouped into series using the Loomis–Wood diagram, however an adjustment of the spectroscopic parameters is not yet possible. Considering a possible assignment of the band observed at 1308.9 cm$^{-1}$ to $\nu_4$ predicted at 1350 cm$^{-1}$ by the ab initio calculations reported in Table 2, we have also conducted an analysis using a-type selection rules in the assignment. While this assignment gives a satisfactory fit as well, the shape of the Q branch in the simulation is much broader and differs significantly from the experimental shape. Therefore the assignment as $\nu_{17}$ seems to be well justified. As in the case of $\nu_{22}$, our data are insufficient to make use of nuclear spin statistical weights in the assignment of $\nu_{17}$.

We have also tested fits with a variation of $D_K$ (and also other parameters) being systematically fixed at a series of values. The conclusion from these tests is that the shape of the Q branch
can be best simulated if all quartic constants are fixed at the values of the quartic constants of the ground state. However, this fixing leads to slightly larger $d_{\text{rms}} = 0.0005$ cm$^{-1}$ which is still below the instrumental resolution. Thus the spectroscopic parameters have clearly a meaning as “effective parameters” only which it does, however, not affect our conclusions.

5.4 Rovibrational analysis and parameters of the $\nu_3$ band of 1,2-dithiine

Consistent with A symmetry under $C_2$, 875 transitions from the $\nu_3$ band were assigned obeying $a$-type selection rules $eo$–$ee$ and $oe$–$oo$ (Fig. 14). These lines were fit with the variation of one more spectroscopic constant than used for the $\nu_{17}$ band. To minimize the possible effects from the observed perturbation in this band, only transitions with $J_{(\text{max})} = 40$ (onset of local resonances) were assigned. There is good agreement between the observed and simulated spectra in unperturbed regions and the band provides a good example for a totally symmetric fundamental.

6 Discussion and conclusions

Designing and selecting molecules towards specific properties for a variety of applications is a well-known task in chemistry. The theoretical selection and spectroscopic characterization of a chiral molecule suitable for the measurement of the parity violating energy difference $\Delta_{pv}E$ between the enantiomers by the method proposed by us three decades ago is a new, very great challenge, given the current technical possibilities. The present work contributes some major results towards this goal, both theoretical and spectroscopic, for the moderately complex molecule 1,2-dithiine.

From the theoretical point of view, we have shown that in the ground and low energy rovibrational states parity violation clearly dominates over tunneling in the quantum dynamics of 1,2-dithiine by many orders of magnitude. Thus the reaction enthalpy $\Delta_{pv}H_0$ for the stereomutation reaction (1) is, in principle, a measurable quantity for 1,2-dithiine, similar to the simpler molecule dichlorodisulfane (Cl–SS–Cl) which we had studied before, and quite different from the case of disulfane HSSH. A detailed study of the conformation dependence of
parity violation in 1,2-dithiine, indeed, shows that this is a particularly favorable molecule, as the maximum of the absolute value of the parity violating potential (about $6 \times 10^{-12} (hc) cm^{-1}$ corresponding to $\Delta_{pv}E^I(q_{\text{max}}) = 12 \times 10^{-12} (hc) cm^{-1}$ in Fig. 4) is found to be close to the equilibrium geometry. The expectation value $\Delta_{pv}E_0$ in the vibrational ground state has been calculated approximately by means of the ground state of the lowest quasidiabatic channel for torsion and differs by less than 10% from the equilibrium value $\Delta_{pv}E^I(q_e) = 11.44 \times 10^{-12} (hc) cm^{-1}$ (eqn (4)), very close to the maximum value. Again, 1,2-dithiine might be compared to CISSCl in this respect where the predicted $\Delta_{pv}E_0$ is smaller by a factor of about 8 ($1.35 \times 10^{-12} (hc) cm^{-1}$), because of the relatively unfavorable position of the equilibrium geometry, far removed from the position of the maximum in the parity violating potential as a function of torsional angle with $\Delta_{pv}E^I(q_{\text{max}}) \approx 12 \times 10^{-12} (hc) cm^{-1}$, which is actually quite similar to the maximum value in 1,2-dithiine. Also in our recent study of $\Delta_{pv}E$ in trisulfane, the predicted $\Delta_{pv}E_0 = 1.6 \times 10^{-12} (hc) cm^{-1}$ is found to be much smaller than the maximum as a function of the torsional (sterior reaction) coordinate $\Delta_{pv}E^I(q_{\text{max}}) = 8.2 \times 10^{-12} (hc) cm^{-1}$). Another, even less favorable example of this kind, which we encountered in the past, is 1,3-difluoroallene which in many other spectroscopic aspects is quite easily accessible.76

Our theoretical results also provide further evidence that simple scaling laws, as repeatedly discussed since the early theoretical work of Bouchiat and Bouchiat62,63 for atoms (with parity violating effects increasing with about the third power of the atomic number $Z$), are of limited significance in predicting parity violation in molecules. Many earlier discussions have pointed out that an approximate scaling with $Z^3$ can be derived for parity violation in molecules31,35,37,61,83 with the implicit assumption that the number of neutrons in a typical nucleus is proportional to $Z$ as well. However, the strong dependence of molecular parity violation upon conformation can easily change the effects by an order of magnitude and more, as seen from the examples given above. Examples are known, where a conformation change in a substituent without changing the stereoreation coordinate can even change the sign of the parity violating potential without changing the enantiomeric nature.33,35,135 Indeed, in strong contrast to atomic parity violation the molecular parity violation is characterized by a complicated ($3N - 6$)-dimensional effective parity violating potential hypersurface to be added to the ordinary parity conserving potential hypersurface as a perturbation of different symmetry.31,35,61 and our results of 1,2-dithiine in relation to other molecules studied demonstrate the complicated consequences of this. It has been pointed out61 that a $Z^3$ scaling might be applied to a series of homologous molecules either at their individual equilibrium geometries or at identical (non-equilibrium) geometries or else at geometries related to the maximum absolute values of $|\Delta_{pv}E^I|$ of the different molecules, with quite different results in each case. As an alternative to the effective parity violating potential one might also consider the tensor components of the parity violating potential61 or values corresponding to the main chiral axes66 in relation to a $Z^3$ scaling. In practice, simple rules including $Z^3$-scaling and geometrical factors might be derived as the first selection criteria,48 but in the end, for individual molecules to be selected for the very demanding experiments, quantitative calculations as carried out here for 1,2-dithiine including the conformation dependence and tunneling processes are required. In this respect, 1,2-dithiine turns out to be quite a favorable candidate for experiments.

Tunneling in the ground state has been shown in the present work to be completely suppressed for 1,2-dithiine with

$$\Delta E_o < 10^{-24} (hc) cm^{-1} \ll \Delta E_{pv} \approx 10^{-11} (hc) cm^{-1} \quad (6)$$

similar to CISSCl, for example.71 However the barrier for stereoremation in 1,2-dithiine is much lower than in CISSCl. Thus in 1,2-dithiine tunneling can become important above about 2300 cm$^{-1}$, making states of well-defined parity accessible in the infrared range, where powerful high resolution lasers are available for parity selection experiments70 and where spectroscopic analyses are possible, making the “infrared route” towards parity violation possible. This does not exclude the possibility of also using the route via excited electronic states possibly with rovibrational preselection, as suggested for 1,3-difluoroallene,76 but too little is known at present concerning the high resolution electronic spectra of 1,2-dithiine for which we plan a more detailed study as well.

We have shown here that high resolution analyses are possible in the infrared range for 1,2-dithiine, with three strong fundamentals $\nu_{12}$ at 623.094 cm$^{-1}$, $\nu_{13}$ at 1544.900 cm$^{-1}$ and $\nu_{17}$ at 1308.873 cm$^{-1}$. The latter band might be used as a starting point for a stepwise two-photon excitation to the $2\nu_{17}$ range at 2600 cm$^{-1}$, where tunneling can be important, if couplings to tunneling sublevels of well-defined parity can be identified. In the future also high resolution analyses of the $2\nu_{17}$ absorptions or the CH stretching polyad at around 3000 cm$^{-1}$ can become possible. Indeed, the overtone of the fundamental $\nu_{17}$ studied here is predicted to show a strong Fermi-resonance with the CH-stretching fundamentals using our ab initio calculations. In all cases a major remaining challenge will be the analysis of rovibrational couplings to tunneling sublevels of well-defined parity. Some first evidence for rovibrational couplings has been seen in the present analysis of $\nu_{17}$. At higher energies intramolecular rovibrational couplings are very likely,119 given the high density of vibrational states, which is about 50 states per cm$^{-1}$ interval at 2600 cm$^{-1}$ and 1300 states per cm$^{-1}$ interval at around 3000 cm$^{-1}$. The corresponding spectroscopic analyses of the resulting complex spectra can be successful, however, with existing high resolution infrared laser spectroscopy of molecular beams, achieving even hyperfine resolution in excited vibrational states of ammonia, for example, (i.e. $\Delta \nu < 1$ MHz around $\nu = 100$ THz or $\Delta \nu < 0.00003$ cm$^{-1}$ at $\nu = 3300$ cm$^{-1}$). Double resonance with IR-lasers70 and GHz spectroscopy103 can also be helpful in this context. We have furthermore carried out extensive calculations on various deuterated isotopomers of 1,2-dithiine, where the CD infrared chromophore makes the wavenumber range just above the tunneling switching range accessible. These results are presented in the ESI† as well.
The study of the lowest frequency fundamentals by synchrotron-based THz (FTIR) spectroscopy is in progress.

The present work thus clearly opens the route towards successful spectroscopic experiments to measure the parity violating energy difference $\Delta_{\text{pv}}E$ in 1,2-dithione with a rather short time $\tau_{\text{pv}} = 1.5\ \text{s}$ for complete parity change in this molecule; the initial time evolution in the ms range would be clearly detectable by the now available techniques.\(^9\) While a simpler molecule with fewer atoms would certainly still be desirable to complete the necessary spectroscopic groundwork, 1,2-dithione has the advantage of a relatively rigid structure apart from the simple spin 1/2 protons with only the rather light C and S nuclei with zero spin, a simple nuclear structure, which is almost ideal for highly accurate theoretical analyses in terms of fundamental parameters of the standard model of particle physics from experimental results, once available.\(^1\)

Acknowledgements

Our work is financially supported by an advanced grant from the ERC, the Schweizerischer Nationalfonds and the ETH Zürich. The research leading to these results had in particular also received funding from the European Union’s Seventh Framework Programme (FP7/2007–20013) ERC grant agreement no. 290925. Very substantial help from Guido Grassi and Fabienne Arn in the synthesis work is gratefully acknowledged. We also acknowledge the help from and enjoyed the discussion with Andreas Schneider and Andres Laso and also support from the COST project MOLIM.

References

56 M. Quack, Faraday Discuss., 2011, 150, 123–127.
89 J. Fabian, M. Mann and M. Petiau, Molecular Modeling Annual, 2000, 6, 177–185.
115 C. M. Western, *PGOPHER, a Program for Simulating Rotational Structure!*, University of Bristol Research Data Repository, Bristol, 2014.