0.17 mmol, 94 %). No PPN$^+$ resonances were observed by ^{1}H NMR spectroscopy. UV/VIS (MeCN): λ (ε) = 210 (6.8×10^4), 233 (2.1×10^4), 260 nm (6×10^3).

[PPN]-**2**: To a solution of Na[PPN]-**2** (100 mg, 0.050 mmol) in warm ethanol (10 mL) was added a solution of $FeCl_3 \cdot 6\,H_2O$ (14 mg, 0.050 mmol) in ethanol (5 mL). The purple reaction solution was stirred for 30 min at 25 °C and then kept at −18 °C for 3 h. Dark purple crystals precipitated which were separated by filtration, recrystallized from ethanol, and dried (m.p. 197 °C) to yield [PPN]-**2** (90 mg, 0.046 mmol, 90 %). Electrospray MS (MeCN), negative-ion mode: *m/z* (%): 1416.0 (100) [**2**]$^-$; VIS (MeCN): λ (ε) = 537 nm (1.4×10^4); EPR (solid, 273 K): $g = 2.1997$.

2: A sample of K$_2$-**2** (100 mg, 0.067 mmol) was dissolved in ethanol (10 mL) and a solution of $FeCl_3 \cdot 6\,H_2O$ (45 mg, 0.166 mmol) in ethanol (5 mL) was added. The reaction mixture turned purple and then dark red. The suspension was stirred for 1 h at room temperature and the precipitate was removed by filtration. The orange-brown solid was recrystallized from ethanol (m.p. 155 °C) to give **2** (80 mg, 0.057 mmol) in 84 % yield. FAB-MS (acetone), negative-ion mode: *m/z* (%): 1324.7 (25) [**2** − CH$_2$Ph]$^-$, 1415.8 (100) [**2**]$^-$, 1506.7 (70) [**2**+CH$_2$Ph]$^-$; ^{11}B NMR (160 MHz, acetone): δ = 43.3 (s); VIS (MeCN): λ (ε) = 467 nm (1.7×10^4).

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[12] a) Cs[PPN]-**2**, triclinic, space group $P\bar{1}$, $a = 9.986(2)$, $b = 14.039(3)$, $c = 18.441(4)$ Å, $\alpha = 90.062(4)$, $\beta = 93.348(3)$, $\gamma = 90.238(4)°$, $V = 2580.6(8)$ Å^3, $Z = 1$, $2\theta_{max} = 56.6°$, $\rho = 1.343$ Mg m^{-3}, $\lambda(Mo_{K\alpha}) = 0.71069$ Å, 100 K. Of the 11 868 uniqe reflections measured, 7291 were considered observed ($I > 2\sigma(I)$). Data were corrected for Lorentz and polarization effects but not for absorption, $\mu = 0.455$ mm^{-1}. The structure was solved by statistical methods. $R = 0.042$, $wR = 0.065$.; b) Crystallographic data (excluding structure factors) for the structures reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-148658 (**2**), CCDC-148659 (Cs[PPN]-**2**) and CCDC-148660 ([PPN]-**2** · C_6H_6). Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (fax: (+44) 1223-336-033; e-mail: deposit@ccdc.cam.ac.uk).

[13] [PPN]-**2** · C_6H_6, triclinic, space group $P\bar{1}$, $a = 17.761(8)$, $b = 18.786(8)$, $c = 20.588(9)$ Å, $\alpha = 65.156(7)$, $\beta = 65.725(8)$, $\gamma = 63.417(8)°$, $V = 5360(4)$ Å^3, $Z = 2$, $2\theta_{max} = 56.66°$, $\rho = 1.259$ Mg m^{-3}, $\lambda(Mo_{K\alpha}) = 0.71069$ Å^3, 100 K. Of the 24 400 unique reflections measured, 14 575 were considered observed ($I > 2\sigma(I)$). Data were corrected for Lorentz and polarization effects but not for absorption, $\mu = 0.106$ mm^{-1}. The structure was solved by statistical methods. $R = 0.073$, $wR = 0.186$.

[14] **2**, triclinic, space group $P\bar{1}$, $a = 10.107(3)$, $b = 15.014(4)$, $c = 15.033(4)$ Å, $\alpha = 114.893(4)$, $\beta = 103.118(5)$, $\gamma = 102.823(5)°$, $V = 1880.8(9)$ Å^3, $Z = 1$, $\rho = 1.25$ Mg m^{-3}, $\lambda(Mo_{K\alpha}) = 0.71069$ Å, 100 K. Of the 11 869 unique reflections measured, 8403 were considered observed ($I > 2\sigma(I)$). Data were corrected for Lorentz and polarization effects, and for absorption, $\mu = 0.079$ mm^{-1}. The structure was solved by statistical methods. $R = 0.048$, $wR = 0.118$.

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Parity Violation in Fluorooxirane[**]

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Dedicated to Professor Paul von Ragué Schleyer
on the occasion of his 70th birthday

Van't Hoff pointed out more than a century ago[1] that the heat of formation and the entropy of enantiomers of chiral molecules must be exactly equal for symmetry reasons. Traditional quantum chemistry which only includes the electromagnetic interaction finds just this symmetry.[2] However, electroweak quantum chemistry which includes parity violation predicts an energy and entropy difference. One of the greatest challenges in the current understanding of fundamental aspects of the structure and dynamics of chiral molecules concerns the experimental proof of the role of parity violation because of the weak nuclear interaction.[3] Experimental spectroscopic approaches have been proposed for some time. One of these approaches is to measure directly the heat of reaction $\Delta_r H_0^0$ for the transformation of S into R enantiomers which is related to the parity violating energy difference $\Delta_{pv}E$[3, 4] as shown in Equation (1).

$$\Delta_r H_0^0 \ (S \rightleftarrows R) \approx N_A \Delta_{pv} E \tag{1}$$

Another approach is measuring certain frequency shifts of the enantiomers, for instance in NMR,[5] microwave,[6] IR,[6–10] or Mößbauer[11] spectra of R and S enantiomers (see the diagram in Figure 1).

The recent theoretical discovery[12, 13] that parity-violating effects in chiral molecules are typically one to two orders of magnitude larger than previously anticipated[14, 15] has stimulated intensified theoretical[16–22] and experimental interest[6, 10, 11] in this field. Of particular importance are experi-

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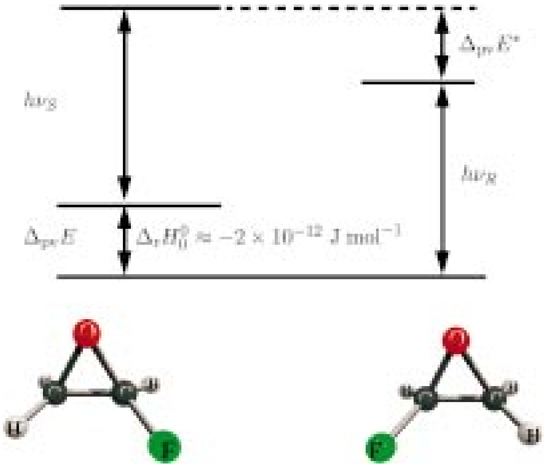

Figure 1. Scheme of energy levels and structures of fluorooxirane enantiomers. The structure of (*R*)-fluorooxirane (right) as used in the calculations was obtained by a full structure optimization using MP2 with a TZ2P basis set and is consistent with experimental data from high-resolution spectra.[24] The dashed line indicates that the direct optical transition to this *S* state from the *R* ground state is forbidden.

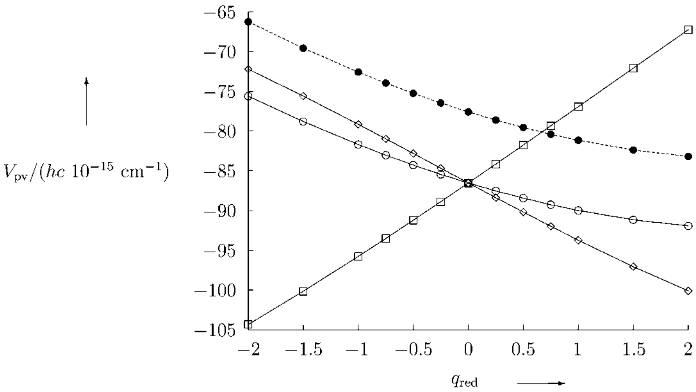

Figure 2. Parity violating potential V_{pv} [10^{-15} cm^{-1}] as obtained for (R)-fluorooxirane from RPA (○, full lines) and CASSCF calculations (●, dashed line) with a triple zeta basis set augmented by two sets of polarization functions (TZ2P). The dimensionless reduced normal coordinate (q_{red}) dependence of V_{pv} is shown for the present choice of vibrational phases of the three modes displayed here (ν_7 (□), ν_8 (◇), ν_9 (○ and ●) correspond to δ-C–F–H bending, δ-CH$_2$ bending, and the C–F stretching mode).[24]

ments on chiral molecules in the low frequency "optical" (infrared[10]) domain, where the currently best relative frequency uncertainty of about 10^{-13} has been obtained in the CO$_2$-laser emission range around 1000 cm^{-1}. This uncertainty is still three to four orders of magnitude greater than the effects calculated for one useful test molecule CHBrClF.[20–22] A prerequisite for any such experiment, as well as for the proposed direct measurement of $\Delta_{pv}E$[4] is a rovibrationally line resolved and analyzed optical spectrum of the chiral molecule under consideration. While until 1994 there was to our knowledge not a single example where such an analysis had been achieved for a chiral molecule, since that time three cases in parallel have been successfully studied in our laboratory: CHBrClF,[6, 23] 2-fluorooxirane,[24] and (2,2-^{2}H$_2$)thiirane-1-oxide.[25, 26]

Fluorooxirane (Figure 1) is a particularly interesting molecule because it contains only atoms of the first row of the periodic table, rendering fundamental and accurate calculations possible. Because of its rather rigid, cyclic structure it has a particularly simple infrared spectrum in the CO$_2$-laser range. Fluorooxirane as well as related compounds might prove to be crucial for future experimental and theoretical efforts. We present here the first calculations on the parity-violating energy difference $\Delta_{pv}E$ as well as vibrational and rotational frequency shifts for this compound.

Our general theoretical approaches to parity violation have been described elsewhere.[13, 19–21] Herein we follow closely our approach used for CHBrClF.[20, 21] Briefly, we have used the multiconfiguration linear response (MC-LR) approach[19] in the random phase approximation (RPA), and complete active space self consistent field (CASSCF) limit.

An estimate of rotational and vibrational frequency shifts between *R* and *S* enantiomers is obtained by using a coordinate dependent parity-violating potential, $V_{pv}(\vec{q})$[20, 21] which has been calculated using RPA (if not specified otherwise). $\vec{q}$ describes a suitable set of molecular coordinates (here, reduced vibrational normal coordinates). Figure 2 shows as an example V_{pv} for three different modes including the C–F stretching vibration ν_9.

By analyzing the coordinate dependence of V_{pv} we are able to calculate estimates for the vibrational wavenumber shifts between (*R*)- and (*S*)-fluorooxirane from the polynomial coefficients used to fit the coordinate-dependent parity-violating potential for each mode *j* of the $3N-6$ vibrational modes, where *N* is the number of atoms ($N=7$).

Table 1 summarizes the most relevant coefficients $p_0(j)$ to $p_2(j)$ from a third-order polynomial fit $V(q_j) \approx \sum_{i=0}^{3} p_i(j)\, q_j^i$, where $p_0(j)$ is related to $\Delta_{pv}E$ by Equation (2).

$$E^{(R)} - E^{(S)} = \Delta_{pv}E = 2 \times V_{pv}(\vec{q}=\vec{0}) \approx 2 \times p_0(j) = 2 \times \tilde{p}_0(j) \times hc \\ \approx -155 \times 10^{-15}\ \text{cm}^{-1} \times hc \tag{2}$$

This corresponds to a value for $\Delta_r H_0^0$ of about -2×10^{-12} J mol^{-1} (obtained with CASSCF). Thus, (*R*)-fluorooxirane is more stable than (*S*)-fluorooxirane. The vibrational wavenumber shift for mode *j* in the separable harmonic adiabatic approximation (SHAA) is given by Equation (3).[21]

$$\Delta_{pv}\tilde{\omega}(j) \ = \ \tilde{\omega}^{(R)}(j) - \tilde{\omega}^{(S)}(j) \ \approx \ 2 \times \tilde{p}_2(j) \tag{3}$$

As shown in Table 1 the value of $\Delta_{pv}\tilde{\omega}/\tilde{\omega}$ is very dependent on the absolute magnitude as well as on the sign of the relative shift. For the C–F stretching mode ν_9 we find Equation (4).

$$\Delta_{pv}\tilde{\omega}_9/\tilde{\omega}_9 \ \approx \ 1.2 \times 10^{-18}. \tag{4}$$

The last column of Table 1 shows anharmonic vibrational wavenumber shifts obtained within the separable anharmonic adiabatic approximation (SAAA)[21] for some selected modes as expectation values of the parity-violating potential V_{pv} with one-dimensional vibrational wavefunctions ($|0'\rangle$ for the ground state and $|1'\rangle$ for the first vibrationally excited state) according to Equation (5).

$$\Delta_{pv}\tilde{\nu}/\tilde{\nu} \ = \ 2 \times (\langle 1' | V_{pv} | 1' \rangle - \langle 0' | V_{pv} | 0' \rangle)/(hc\tilde{\nu}). \tag{5}$$

Table 1. The most relevant parameters $\tilde{p}_0, \tilde{p}_1, \tilde{p}_2$ [10^{-15} cm^{-1}] obtained by fitting the energy points $V_{pv}(q_j)$ calculated ab initio for (R)-fluorooxirane with RPA for each vibrational reduced normal coordinate q_j ($j = 1-15$) to a third-order polynomial. The root-mean-square deviation of the fit to the analytic polynomial is between 10^{-4} and 3×10^{-3}; standard deviation from the fitting procedure are given in parenthesis in units of the last significant digits. The last columns give $\Delta_{pv}\tilde{\omega}/\tilde{\omega}$ and $\Delta_{pv}\tilde{\nu}/\tilde{\nu}$ [10^{-19}] obtained from $\tilde{p}_2$ in the SHAA and for some selected modes in the SAAA.[21] See text for details.

Mode j	ν_{exp}[a] [cm^{-1}]	$\tilde{p}_0$ [10^{-15}cm^{-1}]	$\tilde{p}_1$ [10^{-15}cm^{-1}]	$\tilde{p}_2$ [10^{-15}cm^{-1}]	$\Delta_{pv}\tilde{\omega}/\tilde{\omega}$ [10^{-19}]	$\Delta_{pv}\tilde{\nu}/\tilde{\nu}$ [10^{-19}]
1	3078	– 86.5287(4)	2.7877(6)	– 0.089(2)	– 0.54	
2	3050	– 86.5253(11)	1.8263(16)	0.2223(6)	1.37	
3	3011	– 86.5280(1)	– 1.4644(2)	– 0.1129(1)	– 0.71	
4	1479	– 86.5308(13)	– 2.2998(20)	0.2136(7)	2.77	
5	1383	– 86.5309(14)	1.2452(21)	– 0.3045(7)	– 4.26	
6	1284	– 86.5278(1)	5.1859(1)	0.1871(1)	2.83	
7	1156	– 86.5278(3)	9.4739(4)	0.1848(1)	3.11	5.91
8	1135	– 86.5272(8)	– 7.3957(12)	0.0927(4)	1.59	3.92
9	1126	– 86.5289(5)	– 4.1706(8)	0.6904(3)	12.02	15.15
9	1126	– 77.5797(7)[b]	– 4.3123(10)[b]	0.7149(4)[b]	12.45[b]	15.70[b]
10	1085	– 86.5309(14)	2.0286(22)	0.1605(8)	2.92	3.33
11	968.21267(5)	– 86.5311(15)	10.1087(22)	0.3232(8)	6.56	2.35
12	866.637(3)	– 86.5281(3)	2.2411(4)	1.1911(2)	27.37	26.59
13	755	– 86.5254(10)	– 6.3877(16)	– 0.7525(6)	– 20.05	– 4.26
14	510	– 86.5240(17)	2.5165(25)	– 0.1326(9)	– 5.18	
15	432	– 86.5269(4)	9.9593(6)	0.2311(2)	10.60	

[a] Ref. [24].[b] CASSCF using an active space of six electrons in six orbitals.

Table 2 displays the vibrational wavenumber shifts for selected modes of the dideuterated species 2-fluoro-(3,3-$^2H_2$)-oxirane as obtained within the SHAA and SAAA. With $\Delta_{pv}E$, $\Delta_{pv}E^*$ (Figure 1) can be estimated from Equation (5).

Table 2. Vibrational wavenumber shifts calculated for selected modes of (R)-2-fluoro-(3,3-$^2H_2$)-oxirane. Parity-violating potentials for the polynomial fit have been calculated using the RPA and CASSCF with an active space of six electrons in six orbitals. For the C–F stretch CASSCF (mode 7) gives, $\Delta_{pv}E/hc = 2\tilde{p}_0 \approx -155.155 \times 10^{-15}$ cm^{-1}, as expected, very similar to the value of -155.159×10^{-15} cm^{-1} for the ^{1}H isotopomer.

Mode j	ν_{exp} [cm^{-1}][a]	Method	$\Delta_{pv}\tilde{\omega}/\tilde{\omega}$ [10^{-19}]	$\Delta_{pv}\tilde{\nu}/\tilde{\nu}$ [10^{-19}]
7	1101.32909(3)	RPA	4.6	11.4
		CAS	4.9	12.3
9	982.0232(3)	RPA	15.3	14.2
		CAS	12.9	11.8

[a] From ref. [24].

The parity-violating potential also gives rise to a change in equilibrium geometry which can be used to estimate the relative shift of the rotational constants caused by V_{pv}.[21] The minimum position $\vec{q}_{min}$ in dimensionless reduced normal coordinates is given by Equation (6). The corresponding relative shift[21] $\Delta_{pv}X_e/X_e$ in rotational constants X with $X = A$, B, C is summarized in Table 3 for (R)-fluoroxirane.

$$q_{min}(j) \approx -\frac{\tilde{p}_1(j)}{\tilde{\omega}_j^0} \quad (6)$$

Table 3. Rotational constants X ($X = A$, B, C) [cm^{-1}] determined by experiment and ab initio calculations for (R)-$^1H_3C_2OF$ and dimensionless relative shifts $\Delta_{pv}X_e/X_e$ [10^{-18}] caused by V_{pv}.

X	Exp.[a]	Ab initio (this work)	$\Delta_{pv}X_e/X_e$
A	0.6703127(6)	0.67039	0.105
B	0.2449829(6)	0.24497	– 0.369
C	0.2139151(5)	0.21345	– 0.019

[a] Ref. [24].

We can compare these observable rotational and vibrational wavenumber shifts to those obtained for (R)- and (S)-CHBrClF.[20–22] For the C–F stretching mode of CHBrClF (in the spectral region of the CO_2 laser), Equation (7) applies.

$$|\Delta_{pv}\tilde{\omega}_4/\tilde{\omega}_4| \approx |\Delta_{pv}\tilde{\nu}_4/\tilde{\nu}_4| \approx 8 \times 10^{-17} \quad (7)$$

As is expected from the presence of two relatively heavy nuclei (Cl, Br), this shift is larger than for fluorooxirane. While the frequency shifts of fluorooxirane are too small to be detected by present day techniques, the energy difference between R and S enantiomers indicated by Equation (8) corresponds to a period of motion for parity change $\tau_{\pm}$ of about 200 s with an initial time evolution in the μs to ms range that should be measurable by the technique proposed in reference [4].

$$\tau_{\pm} = h/\Delta_{pv}E \quad (8)$$

According to the estimates presented in reference [4] a value of $\Delta_{pv}E$ would be sufficient to generate a detectable signal for parity change, if the parity-violating energy difference were on the order of the early theoretical estimate for light molecules,[14, 15] $N_A\Delta_{pv}E = 2 \times 10^{-14}$ J mol^{-1}. As the signal at early times increases quadratically with $\Delta_{pv}E$ the value for fluorooxirane calculated here would thus improve the experimental situation by a factor of 10^4. It should be noted that the "motion" of parity change is no simple motion in space (or in normal coordinate space). It rather corresponds to an "isomerization" between delocalized "strange parity isomers" of chiral molecules (see refs. [3, 4, 27] for details). This type of experiment (while difficult to carry out) together with our new theoretical result for $\Delta_{pv}E$, brings measurements of a parity violating energy difference into the realm of the doable. One may compare the present case with the early pioneering experiment on IR frequency shifts also in a "light-atom molecule", camphor, where $\Delta\nu/\nu \approx 10^{-8}$ was achieved.[9] Even if more recent techniques could provide higher resolving power,[10] a full rotational analysis for the IR spectrum of camphor would be more difficult than for fluorooxirane, and the experiment itself does not provide a value for $\Delta_{\mathrm{pv}}E$. The data calculated here are also sufficient for an estimate of the equilibrium constant for racemization[28] from Equations (9) and (10) where x and y explicitly show the deviation from unity of the prefactor and the exponential factor.

$$K_{\mathrm{eq}}^{R,S} = \frac{q_R}{q_S}\exp(-\Delta_{\mathrm{r}}H_0^0/RT) = \frac{q_{\mathrm{vib},R}\,q_{\mathrm{rot},R}}{q_{\mathrm{vib},S}\,q_{\mathrm{rot},S}}\exp(-\Delta_{\mathrm{r}}H_0^0/RT) \quad (9)$$

$$\approx (1+x)(1+y) \quad (10)$$

Within the SHAA ,[20, 21] the equilibrium constant for racemization at 300 K is $K_{\mathrm{eq}}^{R,S} \approx 1 + 8.20 \times 10^{-16}$ with $x \approx -1.01 \times 10^{-17}$ and $y \approx 8.30 \times 10^{-16}$. These values have been obtained with perturbation theory and high precision arithmetic (MAPLE V).[29] To our knowledge, this is the first time that these contributions have been explicitly estimated, although it should be understood that the harmonic approximation is not quite adequate.[28]

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Synthesis of Conformationally Locked Carbohydrates: A Skew-Boat Conformation of L-Iduronic Acid Governs the Antithrombotic Activity of Heparin

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The conformational flexibility[1] of L-iduronic acid, a typical monosaccharide component of heparin, most probably explains its remarkable protein adaptability and resulting diverse biological activities.[2, 3] The analysis of this feature has been the matter of a long controversy,[4] which not surprisingly originates from the complexity of the heparin primary structure. A major breakthrough in heparinology has been the identification,[5, 6] followed by the total synthesis,[7, 8] of a well-defined pentasaccharide sequence inserted into the heparin chain, which specifically binds to antithrombin (AT)—a physiological inhibitor of activated blood coagulation factors—and amplifies its action. This is the molecular origin of the anticoagulant and antithrombotic activities of heparin.

The ^{1}H NMR spectroscopic data of this original synthetic pentasaccharide in aqueous solution were easily extracted and

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