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Parity Violation in Chiral Molecules: From Theory towards Spectroscopic Experiment and the Evolution of Biomolecular Homochirality[a)]

M. Quack*, G. Seyfang and G. Wichmann

Physical Chemistry, ETH Zürich,
CH-8093 Zurich, Switzerland
**E-mail: Martin@Quack.CH*
www.ir.ETHz.CH

Molecular chirality is related to the symmetry with respect to space inversion, which was assumed to be fundamental in the theory of chemical bonding and stereochemistry. The symmetry leads to a conservation law for the quantum number parity as a constant of the motion. We know today that there is in fact a slight asymmetry, which leads to a non-conservation of parity or parity violation. We start with an introductory discussion of three fundamental questions on symmetry, relating physics to molecular quantum dynamics and stereochemistry: (*i*) To what extent are the fundamental symmetries and conservation laws of physics and their violations reflected in molecular quantum dynamics and spectroscopy, in general? (*ii*) How important is parity violation - the violation of space inversion symmetry - for the quantum dynamics and spectroscopy of chiral molecules, in particular? (*iii*) How important is parity violation for biomolecular homochirality, i.e. the quasi exclusive preference of L-amino acids and D-sugars in the biopolymers of life (proteins and DNA)? The observation of biomolecular homochirality can be considered to be a quasi-fossil of the evolution of life, the interpretation of which has been an open question for more than a century, with numerous related hypotheses, but no definitive answers. We shall briefly discuss the current status and the relation to the other two questions. The discovery of parity violation led to important developments of physics in the 20th century and is understood within the standard model of particle physics, SMPP. For molecular stereochemistry it leads to the surprising prediction of a small energy difference D of the ground state energies of the enantiomers of chiral molecules, corresponding to a small reaction enthalpy for the stereomutation between the R and S isomers(enantiomers). With exact parity conservation this reaction enthalpy would be exactly zero by symmetry. Theory predicts D to be in the sub-femto eV range, typically, depending on the molecule (about $D = 200 \pm 50\,\mathrm{aeV}$ for ClSSCl or CHFClBr, corresponding to a reaction enthalpy of about $20 \pm 5\,\mathrm{pJ/mol}$). We have outlined four decades ago, how this small energy difference D might by measured by spectroscopic experiments, and recent progress indicates that experiments might be successful in the near future. We report here about the development of the quantitative theory for predicting D and we then discuss the development and current status of our experiments including alternatives pursued in other groups and the possible consequences for our understanding of molecular and biomolecular chirality as well as the design of molecular quantum switches for a possible future quantum technology and possible tests of CPT symmetry.

Keywords: chiral molecules, parity violation, symmetry, high resolution spectroscopy, biomolecular homochirality

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[a)] Dedicated to the memory of Richard R. Ernst (14 August 1933 - 4 June 2021 (NP Chemistry 1991) after lecture presented at Nobel Symposium 167 on chiral matter, Stockholm, Sweden 28 June - 1 July 2021)

1. Introduction

Ryoji Noyori started his Nobel prize lecture [1] with the sentence: ‘Chirality (handedness, left or right) is an intrinsic universal feature of various levels of matter’, and this sentence can, indeed, serve as a perfect motto for the Nobel Symposium 167 on ‘Chiral Matter’, in general terms. However, the terminology ‘chiral’ (‘handed’, from the ancient Greek $\chi\varepsilon\iota\varrho$, cheir, for hand) was introduced in the context of the structure and chemistry of chiral molecules [2, 3] replacing the earlier terminology ‘dissymmetric’, which was used by Pasteur, the discoverer of molecular chirality [4–7].

Molecular chirality is of fundamental importance in stereochemistry and has, indeed, been crucial in the development of our understanding of the foundations of physical-chemical stereochemistry [8]. Advances in the understanding and uses of chiral molecules are reflected by numerous Nobel prizes over more than a century beginning with the first to van’t Hoff (1901, a founder of the field of stereochemistry while his research on chemical dynamics and osmotic pressure was emphasized in the prize citation) shortly thereafter to Emil Fischer (1902, emphasizing also his work on organic stereochemistry), and Alfred Werner (1913) [4, 9]. More recently we may mention V. Prelog in 1975 [10], W. S. Knowles, R. Noyori, and K. B. Sharpless in 2001 [1, 11, 12] or the most recent one in 2021 [13, 14] as selected examples. Also molecular motors contain an important ‘chiral’ aspect [15–17]. Chiral molecules are standard textbook [18] and examination topics in chemistry testing knowledge of chemical nomenclature [19] and at the same time they are of crucial importance in chemical and pharmaceutical industry (see Refs. 20, 21 for example), see also the lecture by Sarah Price at this symposium.

At the same time chiral molecules have a deep connection to the foundations of physics through symmetries and conservation laws [22–24]. Symmetries are very general underlying ordering principles in the systematic approach to understanding nature or even external reality as such, which is assumed to exist as a premiss in science. Starting from observed facts (in experiments or otherwise by ‘observations’, for instance in astronomy) one has to organize these in well ordered mental ‘pictures’, which may be called models, hypotheses or theories at various levels of understanding (see Fig. 1). It turns out that symmetries and their violation by asymmetries provide a further underlying structure of these and can even be related to the fundamental question of ‘observability’ of certain basic facts of theoretical structures as we shall see in Sec. 2. In this sense, symmetries and asymmetries have a very special role for the structure of theory. Indeed, the discovery of the violation of space inversion symmetry, one of the fundamental symmetries of physics, or ‘parity violation’ in nuclear and elementary particle physics [25–30] not only led to the development of the current ‘Standard Model of Particle Physics’ (SMPP) [31–37], but also to an interesting interaction between high energy physics, molecular physics, chemistry, and also biochemistry and biology [38, 39]. This interaction results in the following at first perhaps surprising statements [40].

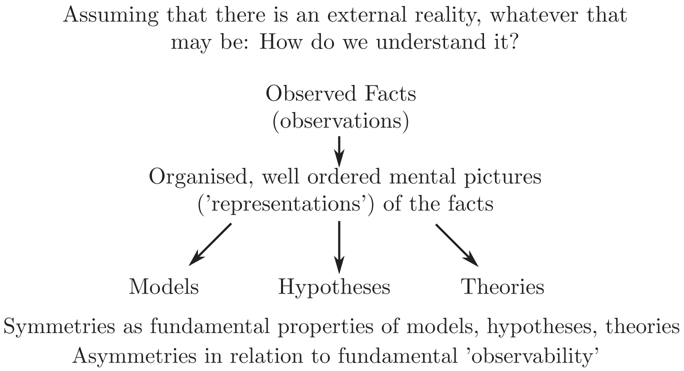


Fig. 1. Organising the facts of reality by models, hypotheses and theories, with symmetries and asymmetries as common fundamental properties (after Ref. 44).

(1) The fundamentally new physics arising from parity violation and the consequent electroweak theory in the SMPP leads to the prediction of fundamental new effects in the dynamics of chiral molecules and thus in the realm of chemistry.
(2) Possible experiments on parity violation in chiral molecules open a new and very special window to looking at the fundamental symmetries of nature and certain aspects of the standard model of high energy physics, and thus molecular physics might contribute to our understanding of the fundamental laws of physics.
(3) Parity violation in chiral molecules provides a unique and very special connection to the early evolution of life as we know it (through the 'homochirality' in the biopolymers of life, which select L-amino acids and D-sugars with absolute preference). This has possibly (but not necessarily) important consequences for the early evolution of life.

Indeed, going beyond parity violation and the standard model, molecular chirality may provide a fresh look at time reversal symmetry and its violation and even the nature of time [41–43].

In the present contribution to this symposium we shall start in Sec. 2 with a conceptual discussion of the use of symmetries in understanding molecular quantum dynamics in general and for chiral molecules in particular. We shall then describe the long road from the idea for an experimental concept to the development of a quantitative theory of parity violation in chiral molecules (Sec. 3) and current developments in spectroscopic experiments on chiral molecules and parity violation (Sec. 4). We shall conclude with a very brief summary of considerations concerning the evolution of biomolecular homochirality (Sec. 5). We restrict attention in this short article on the fundamental concepts and the most important developments as they lead to the current status in the field. We refer to extensive reviews and books in the past for further background and more complete references [22, 23, 38–40, 44–51].

We conclude this brief introduction with a historical remark concerning an important statement by van't Hoff [52] who clearly expressed the consequences for the energetic and thermodynamic equivalence of the enantiomers arising from symmetry (Fig. 2). Considering the equilibrium in the reaction between R and S (a 'stereomutation reaction') he writes:

$$\mathrm{S(L)} \rightleftharpoons \mathrm{R(D)} \tag{1}$$

and states that the equilibrium constant must be exactly 1 by symmetry

$$K = [\mathrm{R}]/[\mathrm{S}] = 1 \tag{2}$$

$$\ln K = -\Delta_\mathrm{R} S^\ominus(T)/(\mathrm{R}T) = 0 \quad \text{all } T \tag{3}$$

We show in Fig. 2 the original citation with its translation and have rewritten here van't Hoff's equations in modern notation. Because of the 'exact symmetry', as he writes, the ground state energies of the enantiomer (E^o_R and E^o_S) and all reaction energies $\Delta_\mathrm{R}H^\ominus$, $\Delta_\mathrm{R}G^\ominus$ and entropies ($\Delta_\mathrm{R}S^\ominus$) must be zero (see [45] for further discussion).

We anticipate here an important change which arose from developments in high energy physics of the second half of the 20th century. We know now that there is no such exact symmetry and in actual fact there is a slight 'parity violating' energy difference $D = \Delta_\mathrm{pv}E$ between the ground states of the enantiomers, say

$$\Delta_\mathrm{pv}E = E^\mathrm{o}_\mathrm{R} - E^\mathrm{o}_\mathrm{S} = \Delta_\mathrm{R}H^\ominus_0/N_\mathrm{A} \tag{4}$$

and small non-zero absolute values also for all the thermodynamic quantities mentioned above [53] ($\Delta_\mathrm{R}G^\ominus$, $\Delta_\mathrm{R}H^\ominus$, $\Delta_\mathrm{R}S^\ominus$, etc.). This is shown schematically in

J. H. van't Hoff 'La Chimie dans l'espace' **1887**

$$\mathrm{S} \rightleftharpoons \mathrm{R}$$

'... Un tel équilibre dépend du travail (E) que la transformation peut produire, travail, qui doit être égal à zéro dans le cas en question, vue la symétrie mécanique parfaite des deux isomères...'

'Such an equilibrium depends upon the work (E) which the transformation can generate, work which must be equal to zero in this case, in view of the perfect mechanical symmetry of the two isomers...'

$\ln K = -\frac{\Delta_\mathrm{R}G^\ominus}{\mathrm{R}T} = 0$

$\Delta_\mathrm{R}S^\ominus$ and $\Delta_\mathrm{R}H^\ominus$ are exactly zero at all T.

$E^0_\mathrm{S} = E^0_\mathrm{R}$

But today $\Delta_\mathrm{R}H^\ominus_0 \neq 0$ due to parity violation!

Very small, but how small or how big exactly?

Fig. 2. The text from the original publication [52] of van't Hoff stating that the mirror symmetry between the enantiomers S and R of a chiral molecule has consequences for energies and equilibria, rewritten as equations in modern notation replacing 'work E' by the Gibbs free energy $\Delta_\mathrm{R}G^\ominus$ (after Ref. 45).

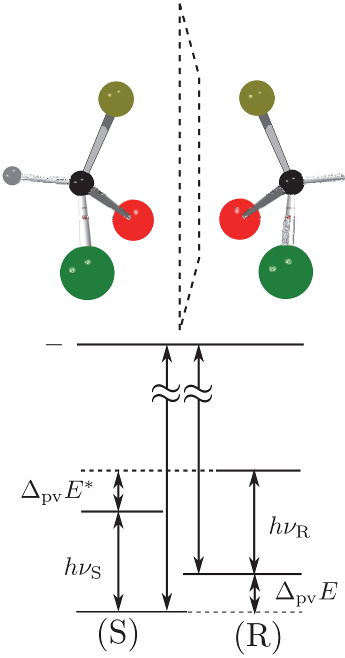


Fig. 3. Energy level scheme for the two enantiomers of CHFClBr including parity violation (see Refs. 39, 47). Following Refs. 54, 55 (S) is calculated to be more stable than (R) by $\Delta_{\mathrm{pv}}E \simeq$ 236 aeV corresponding to about $\Delta_{\mathrm{R}}H^{\ominus} \simeq 23 \cdot 10^{-12}$ J/mol (23 pJ/mol).

Fig. 3 for the example of CHFClBr which will be discussed in the following sections in detail, and which had already used by van't Hoff as a prototype chiral molecule [8].

2. Symmetries, symmetry violations and approximate constants of the motion

The time evolution of a molecular system can be described by the time dependent Schrödinger equation [56–59]:

$$\mathbf{i}\frac{h}{2\pi}\frac{\partial\Psi(q,t)}{\partial t} = \hat{H}\Psi(q,t) \tag{5}$$

with the Hamilton operator $\hat{H}$

$$\hat{H} = \hat{T} + \hat{V}(q) \tag{6}$$

as sum of kinetic energy operator $\hat{T}$ and potential energy $\hat{V}(q)$, where q is considered to represent the complete set of space and spin coordinates applicable for the molecule under consideration and is simply one coordinate for a one dimensional model problem. For an isolated molecule the solution of Eq. (5) can be written as

$$\Psi(q,t) = \sum_{k=1}^{\infty} c_k \varphi_k(q) \exp(-2\pi \mathbf{i} E_k t/h) \tag{7}$$

with time independent generally complex coefficients c_k. Here the $\varphi_k(q)$ and E_k are obtained from the solution of the time independent Schrödinger equation

$$\hat{H}\varphi_k(q) = E_k \varphi_k(q) \tag{8}$$

From the time dependent wave functions $\Psi(q,t)$ and also the time independent wave function $\varphi_k(q)$ as special case, one can obtain relevant time dependent observable quantities, for example the probability density $P(q,t)$ for the molecular 'structure':

$$P(q,t) = |\Psi(q,t)|^2 \tag{9}$$

$$p_k(q) = |\varphi_k(q)|^2 \tag{10}$$

The time evolution of a molecular (or any other 'microscopic') system according to the Schrödinger equation (Eq. (5)) can also be written in a general abstract way by means of the time evolution operator $\hat{U}(t,t_0)$ [50, 51, 60]:

$$\Psi(q,t) = \hat{U}(t,t_0)\Psi(q,t_0) \tag{11}$$

This operator transforms the wave function $\Psi(q,t_0)$ at the initial time t_0 to the wave function $\Psi(q,t)$ at time t. $\hat{U}$ satisfies a differential equation analogous to Eq. (5) and for an isolated system with a time independent $\hat{H}$ it is given by an exponential function of $\hat{H}$:

$$\hat{U}(t,t_0) = \exp\left[-2\pi \mathbf{i} \hat{H}(t-t_0)/h\right] \tag{12}$$

For solutions with a more general time-dependent $\hat{H}$ see [50, 51, 60–62]. Another representation of time dependence in quantum dynamics makes use of the Heisenberg equations of motion [63, 64] for the operator $\hat{Q}(t)$ related to some observable Q, with the solution

$$\hat{Q}(t) = \hat{U}^{\dagger}(t,t_0)\hat{Q}(t_0)\hat{U}(t,t_0) \tag{13}$$

Instead of asking about the time dependence of observables, of which there are many, one might ask the opposite question, whether in a complex time evolving system there are observables which remain constant in time, the 'constants of the motion'. These are all the observables C_j for which the corresponding operators $\hat{C}_j$ commute with the Hamiltonian $\hat{H}$

$$\hat{H}\hat{C}_j = \hat{C}_j\hat{H} \tag{14}$$

Making use of the solution of the Heisenberg equations of motion given by Eq. (13) the time independence of $\hat{C}_j$ can be proven in one line, because $\hat{U}$ being a function of $\hat{H}$, Eq. (12), it commutes with the $\hat{C}_j$ as well and it is also unitary $\hat{U}^\dagger \hat{U} = 1$, thus:

$$\hat{C}_j = \hat{U}^\dagger(t, t_0)\hat{C}_j(t_0)\hat{U}(t, t_0) = \hat{U}^\dagger(t, t_0)\hat{U}(t, t_0)\hat{C}_j(t_0) = \hat{C}_j(t_0) \tag{15}$$

The operators $\hat{C}_j$ form a group G, the symmetry group of the Hamiltonian [23, 50, 60]. One can furthermore show that for a statistical ensemble described by the density operator $\hat{\varrho}$ also the expectation values $\langle \hat{C}_j(t) \rangle = \mathrm{tr}(\hat{\varrho}\hat{C}_j)$ are time independent. Also, if $\Psi(q, t)$ is an eigenfunction $\zeta_n(t)$ of $\hat{C}_j$ with eigenvalue C_{jn} one has

$$\langle \hat{C}_j(t) \rangle = \langle \zeta_n(t) | \hat{C}_j(t_0) | \zeta_n(t) \rangle = C_{jn} \tag{16}$$

The eigenvalues C_{jn} are 'good quantum numbers' not changing in time. While this allows one to identify some simple structures, which do not change with time even in very complex time-dependent systems, one can proceed further by separating the Hamiltonian into contributions of different magnitude ($\hat{H}_0 \gg \hat{H}_1 \gg \hat{H}_2$ etc.)

$$\hat{H} = \hat{H}_0 + \hat{H}_1 + \hat{H}_2 + ... \tag{17}$$

Then the energy levels of a molecule, say, would be described to a good approximation by $\hat{H}_0$, and when adding $\hat{H}_1$, this would change the energy only a little, being a small 'perturbation'. The symmetry group G of the Hamiltonian may now depend on which terms are retained in Eq. (17), with groups $G_0(\hat{H}_0)$, $G_1(\hat{H}_0 + \hat{H}_1)$, $G_2(\hat{H}_0 + \hat{H}_1 + \hat{H}_2)$, etc.. Then one can have a symmetry or constant of the motion $\hat{C}_{0j}$ belonging to $G_0(\hat{H}_0)$ which may not appear in $G_1(\hat{H}_0 + \hat{H}_1)$. Thus, if one observes a change in time for this observable corresponding to $\hat{C}_{0j}$, this cannot be due to $\hat{H}_0$, as $\hat{C}_{0j}$ would be exactly time independent if only $\hat{H}_0$ is considered. The change of $\hat{C}_{0j}$ in time must entirely arise from $\hat{H}_1$ (or $\hat{H}_2$, if any). At the same time, the different magnitudes of the contributions in $\hat{H}$ introduce a natural hierarchy of time scales, $\hat{H}_0$ leading to some possibly very fast changes for some observables but no change in $\hat{C}_{0j}$, the small $\hat{H}_1$ introducing a slow change of $\hat{C}_{0j}$, and so forth. This allows one to isolate very small contributions in the Hamiltonian arising from $\hat{H}_1$ independent of any large uncertainties, which may occur in the very large $\hat{H}_0$. To use a common picture: One can weigh the 'captain' directly without having to measure a difference in the weight of 'ship+captain' and 'ship alone', where the uncertainty in the latter measurement would be much larger than any possible weight of a captain. For the example of parity violation we shall have differences on the order of magnitude of typical electronic energies of molecules (say, on the order of 1 eV) compared to parity violating energies on the order of 100 aeV to 1 feV, more than 15 orders of magnitude smaller. One may compare this with the weight of a large ship (for example Queen Elisabeth 2) with about 50'000 tons displacement and a captain with 50 to 100 kg, less than 6 orders of magnitude difference.

This concept can be made use of for theory, where the uncertainties in solutions of the Schrödinger equation may be due to theoretical or just numerical

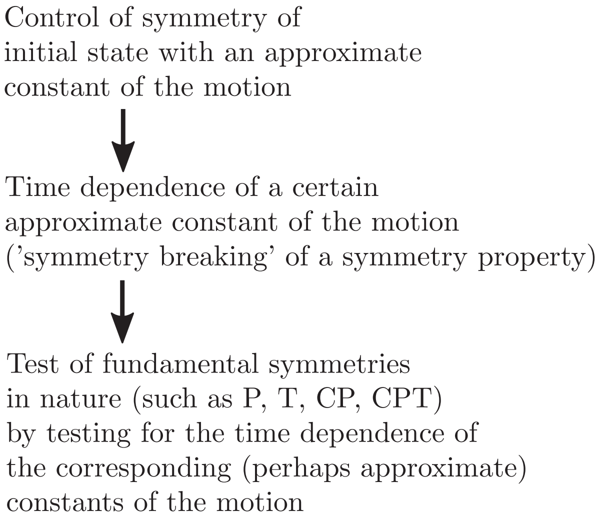


Fig. 4. Scheme for control of symmetries and time evolution in molecular dynamics (modified after Ref. [65], see also Refs. [47, 66]).

uncertainties, typically much larger than a fraction of 10^{-15}: In quantum chemical calculations an uncertainty of 1 meV (in $\hat{H}_0$) would be considered quite acceptable, but is huge compared to 1 feV. The concept can also be made use of in the design of experiments, where a relative experimental uncertainty of less than 10^{-15} may be very difficult to achieve otherwise.

In a time dependent experiment one would follow the scheme of Fig. 4. One prepares a state of a given symmetry corresponding to a 'good quantum number' with respect to $\hat{H}_0$, and then follows the time dependence of this quantum number to observe an effect exclusively due to $\hat{H}_1$ etc. This scheme can be used by means of various kinds of approximate symmetries such as nuclear spin symmetry [67, 68] or one can consider some specific symmetries from simplified molecular models for intramolecular vibrational energy flow in polyatomic molecules, for instance, and we have made extensive use of it in the past (see [62, 67–70] and our recent review [47], for example). Table 1 summarises some results from our work.

However, the approach can also be used for testing fundamental symmetries of physics. These are given by the invariances of the Hamiltonian under [23]

(1) Any translation in space
(2) Any translation in time
(3) Any rotation in space
(4) The reflection of all coordinates of all particles on the center of mass of the system ('P')
(5) 'Time reversal' (reversal of momenta and spins) ('T')

Table 1. Time scales for intramolecular primary processes as successive 'symmetry breakings' for different approximate constants of the motion (modified after Refs. 23, 66, 75, see also Ref. 47).

Approximate constant of the motion	Symmetry breaking process (selected references)	Time scale
Quantum numbers of separate harmonic oscillators (for harmonic approximation in polyatomic molecules)	Selective vibrational stretch-bend Fermi resonance in R_3CH [62, 76–83]	10-200 fs
	Ordinary, weakly selective anharmonic couplings [62, 76, 83–86]	500 fs – 10 ps
Quantum numbers of adiabatically separable anharmonic oscillators	'Vibrationally non-adiabatic' couplings $R–C \equiv C–H$, HF-HF [62, 66, 75, 76, 80, 87–92] Δl coupling in C_{3v} symmetric tops R_3CH [70]	10 ps-1 ns
Structural identity for structures separated by high BO barriers	Tunneling processes [46, 93–97, 117]	< 1 ps to very long
Nuclear spin symmetry (separable nuclear spin-rotation-vibration states)	Violation of nuclear spin symmetry (rotation-vibration nuclear spin coupling) [23, 67, 98, 99]	1 ns – 1 s
Parity (space inversion symmetry)	Parity violation [23, 38, 54, 67, 100–105]	1 ms – 1 ks (theory only)
Time reversal symmetry T	T-violation in chiral and achiral molecules? [23, 42, 43, 62, 75, 87, 106–109]	Molecular time scale not known (neither quantitative theory nor experiment) but known in SMPP
CPT Symmetry	Hypothetical CPT violation [23, 43, 87, 106, 107]	So far not found in any part of physics

(6) Any permutation of identical particles (electrons or nuclei for the case of molecules)

(7) Charge conjugation - the replacement of all particles by the corresponding antiparticles ('C')

The symmetries are related to the corresponding conservation laws (for momentum, energy, angular momentum, parity,...) as has been discussed early on in quantum mechanics [71, 72] and in an interesting summary by Pauli [73] for the three discrete symmetry operations C, P, T, which one may all consider as some kind of generalised 'mirror symmetry'. Fig. 5 illustrates this for the case of the parity symmetry ('P' one uses also the symbol E^* for the operation of space inversion in molecular physics [74]).

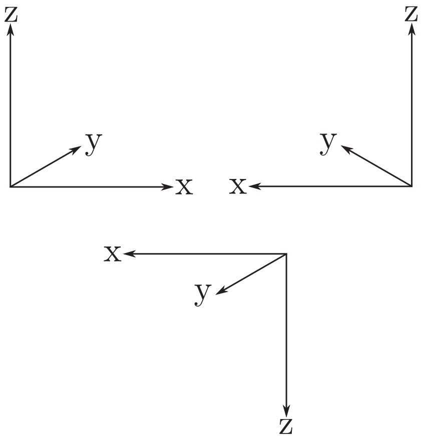
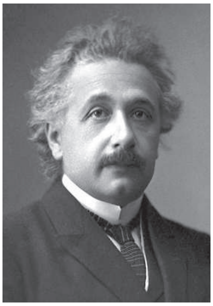


Fig. 5. ‘Right handed’ Cartesian coordinate system (upper left), mirror image (upper right) and inverted (lower) coordinate systems being ‘left handed’.

The inversion of the right handed coordinate system in the upper left part (as defined by the ‘right hand rule’ convention) by a mirror leads to the left handed coordinate system on the upper right side. The space inversion or parity operator on the right handed coordinate system changes ($x \to -x$, $y \to -y$, $z \to -z$) into a left handed system as shown in the lower part. This can be transformed to the left handed ‘mirror’ image on the upper right by a rotation of 180° around the x axis, which corresponds to one of the symmetry operations under (3), the combination being obviously also a symmetry operation for the Hamiltonian, leading to a related constant of the motion, the space inversion P being the elementary operation. A further interesting aspect is the notion that each exact symmetry and conservation law leads to a fundamental ‘non-observable’ property of nature. This can be nicely understood with the statement by Einstein [110] (original in German, as shown in Fig. 6, as translated in [23]):

‘There are thus two types of Cartesian coordinate systems, which are called ‘right-handed’ and ‘left-handed’ systems. The difference between the two is familiar to every physicist and engineer. It is interesting that an absolute geometric definition of the right or left handedness is impossible, only the relationship of opposition between the two can be defined’.

For chiral molecules this implies that even if we can determine the ‘absolute’ configuration of a molecule in comparison to a macroscopic model in the laboratory, we cannot specify for either of the two whether they occur in a space with a left handed or right handed coordinate system. One way to illustrate this property of ‘non-observability’ is the so called ‘Ozma’ problem [41, 111]: If there were perfect space inversion symmetry, we would not be able to communicate to a distant civilization with a coded message (without sending a real chiral ‘model’), whether we are made of L-amino acids or of D-amino acids, for instance. This is another way of phrasing Einstein’s statement. Van’t Hoff and Einstein assumed space inversion



'Non-observability' of 'left-right' structure
'Nichtbeobachtbarkeit' der absoluten 'Rechts- oder Linkshändigkeit' des Raumes
bei perfekter Spiegelsymmetrie

Es gibt also zweierlei kartesische Koordinatensysteme, welche man als 'Rechtssysteme' und 'Linkssysteme' bezeichnet. Der Unterschied zwischen beiden ist jedem Physiker und Ingenieur geläufig.

***Interessant ist, dass man Rechtssysteme bzw. Linkssysteme an sich nicht geometrisch definieren kann*, wohl aber die Gegensätzlichkeit beider Systeme.**
Albert Einstein (ML, 1922)

Non-observability due to a symmetry, but today we know, that the symmetry is violated, handedness of space can be 'observed absolutely' and communicated in an absolute sense (by experiments in nuclear and high energy physics). One alternative experimental approach uses high resolution spectroscopy of chiral molecules and parity violation by the electroweak interaction.

Fig. 6. On the non-observability of absolute handedness with perfect mirror symmetry and parity conservation (citation from Ref. 110 after Ref. 23, 48).

symmetry to be universally valid and thus the 'handedness' of space would be 'non-observable'. This was the common assumption until 1956/57, when parity violation was proposed and observed. Electroweak parity violation makes absolute handedness observable and removes a constant of motion and 'good quantum number' (parity). We have for the 'electromagnetic Hamiltonian' $\hat{H}_{\mathrm{em}}$

$$\hat{H}_{\mathrm{em}}\hat{P} = \hat{P}\hat{H}_{\mathrm{em}} \tag{18}$$

with common eigenfunctions of energy and parity, where the eigenvalues of parity are $+1$ or -1 according to

$$\hat{P}\psi_k = (+1)\psi_k \tag{19}$$

$$\hat{P}\psi_j = (-1)\psi_j \tag{20}$$

The eigenfunctions of the Hamiltonian either are symmetric under space inversion (positive parity $+1$) or antisymmetric under inversion (negative parity -1). With electroweak parity violation due to the weak nuclear force we have $\hat{H}_{\mathrm{em}}+\hat{H}_{\mathrm{weak}}$

$$(\hat{H}_{\mathrm{em}} + \hat{H}_{\mathrm{weak}})\hat{P} \neq \hat{P}(\hat{H}_{\mathrm{em}} + \hat{H}_{\mathrm{weak}}) \tag{21}$$

One consequence is now that the ground state eigenfunctions of chiral molecules are localized and have no well defined parity as shown in the right hand part of Fig. 7 and the two states have different energies. Given this, the 'handedness' of space

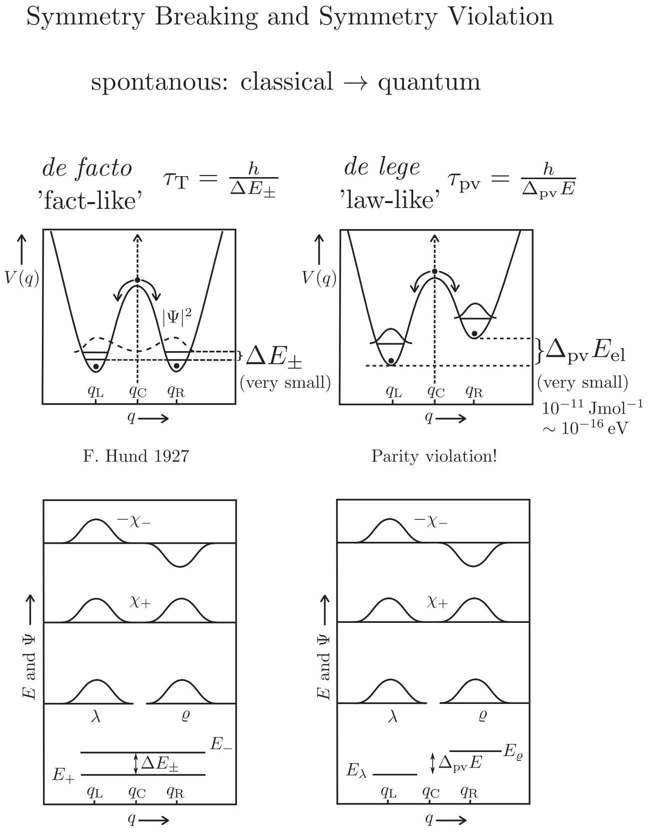
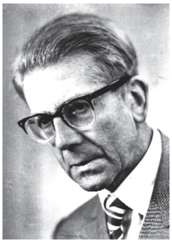


Fig. 7. Illustration of the symmetric (parity conserving) potential on the left side following Hund 1927 for a chiral molecule with energy eigenstates of positive and negative parity separated by a tunneling splitting $\Delta E_\pm$ and for an effective potential with parity violation on the right side leading to two localized ground states at the chiral structures separated by the parity violating energy difference $\Delta_{pv}E$ (after [46], see also [100, 112]).

becomes ‘observable’ and we can communicate to a distant civilization of what type of amino acids we are made of predominantly (for instance the more stable ones, if that is established experimentally, see below). While the energy differences are truly minute, due to ‘weakness’ of $\hat{H}_{weak}$, we can nevertheless compute them significantly and devise significant experiments, because of the different symmetries of $\hat{H}_{em}$ and $\hat{H}_{weak}$, as discussed above. The different symmetry ‘isolates’ the effect of parity violation. We shall in Sec. 3 report on the development of the quantitative theory of parity violation and in Sec. 4 on the current development of experiments.

Before addressing theory and experiment in more detail it is necessary to discuss the quantum dynamics of chiral molecules taking also the order of magnitude of the symmetry violations into account. Figure 7 presents a simple one dimensional quantum mechanical model for the case of the symmetrical electromagnetic Hamiltonian $\hat{H}_{em}$, represented by a symmetrical potential $V(q)$ for the interconversion of the

Friedrich Hund (ML): Discovered Tunnel Effect 1927
with quantum dynamics of chiral molecules
Die Begreifbarkeit der Natur: Understanding Nature (1957)



Geist	Mind spirit
Seele	Soul
Leben	Life
Physikalisch-Chemische Prozesse	Physical-Chemical Processes
Atom	Atom
Elementarteilchen	Elementary Particles
Elementare Materie	Elementary Matter ('SMPP')

Friedrich Hund (1957): Can this continued at the bottom?
Martin Quack (1990): Yes by Geist=Underlying Fundamental Laws=Mind

Fig. 8. Friedrich Hund discovered the tunnel effect in 1927 in his investigations of the quantum dynamics of chiral molecules [113, 114]. He also discussed the stability of biomolecular chirality. The quoted text is from his lecture on understanding nature in 1957, where he considers physical-chemical processes as mediators between atomic and elementary particle physics and life (modified after Ref. 44 with translation from there, see also Ref. 40).

enantiomers (with the 'physical' notation 'left' enantiomer located at the potential minimum of the potential at q_{L} and 'right' at the minimum at q_{R}). Friedrich Hund (Fig. 8) treated the quantum mechanics of chiral molecules under the assumption of a symmetrical Hamiltonian as represented on the left hand side of Fig. 7.

He demonstrated, that the quantum mechanical behaviour of chiral molecules differed considerably from what one expects on the basis of the classical mechanical structural models [113, 114]. Let us consider in Fig. 9 as an example hydrogen-peroxide HOOH which in its equilibrium structure shows axial chirality with the two enantiomers shown (also considered as helical in analogy to the two snails shown in Fig. 9, we note that the two natural snails are not enantiomers at the microscopic level, both having proteins with the L-amino acids and DNA with D-sugars. According to Brunner, the D-sugar DNA leads to a preference of the structure on the left with respect to the right one of 20'000:1 [115, 116]). It turns out that this description with quasi-rigid localized structures is quite inadequate for HOOH in quantum mechanics. By continuously changing the torsional angle indicated in Fig. 9, one can transform one enantiomer into the other: Such a transformation from one enantiomer into the other is also possible in chiral molecules with a pyramidal, near tetrahedral structure as shown in Fig. 10 for the example of the ammonia isotopomer NHDT, where such a 'stereomutation' can be achieved by changing the angle with respect to a planar geometry of the four atoms. Such an 'inversion' in ammonia (NH_3) was actually discussed by Hund and the simple one dimensional model as discussed by him entered the textbooks.

The transformation via planar transition structures in both examples is associated with a potential energy change shown in Fig. 7 schematically.

One may represent the stereomutation reaction from L to R (using the 'physical' notation left to right) by the motion of an effective mass in a potential energy $V(q)$ as a function of the generalized coordinate q. In the time independent Schrödinger

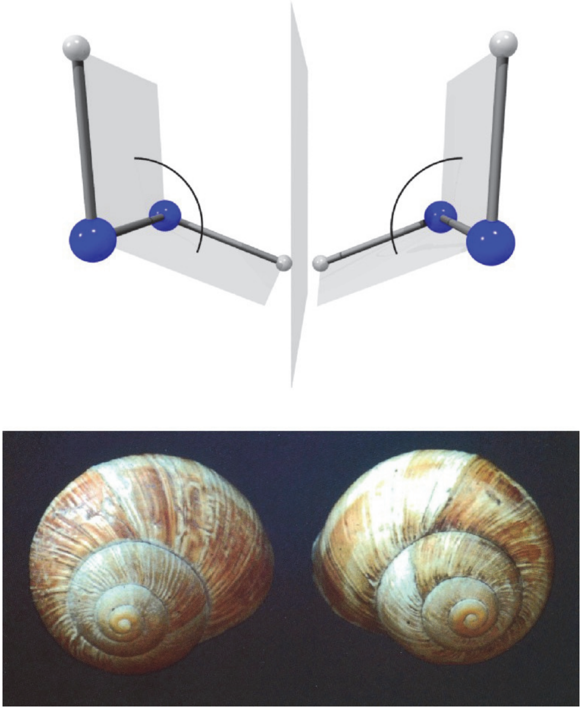


Fig. 9. The classical chiral structures of hydrogen-peroxide H-O-O-H and of snails (as example of axial or helical chirality, after [48]).

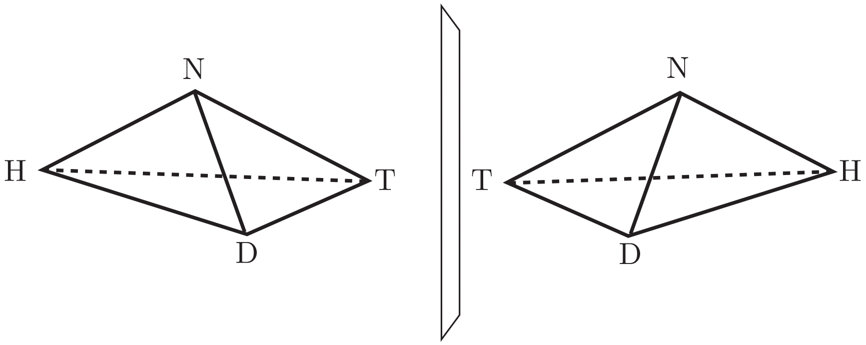


Fig. 10. The classical structures of the chiral enantiomers of the ammonia isotopomer NHDT (after [48]).

equation, Eq. (8), with an exactly symmetrical potential as shown on the left hand side of Fig. 7, the eigenfunctions must be either symmetrical (with 'positive parity' χ_+) or antisymmetrical (with 'negative parity', say $-\chi_-$) with respect to reflection at the 'mirror plane' situated at the center position q_c corresponding to a maximum in the potential energy ($V(q)$). Instead of a well defined structure one has in quantum mechanics quite generally a probability density $p_k(q)$ of finding a structure 'q' in the eigenfunction $\varphi_k(q)$ (with the square of the absolute magnitude $|\varphi_k|^2$, Eq. (10)).

It is seen that for the lowest energy levels (χ_+ at E_+ and χ_- at E_-) shown in the diagram this probability density has two equal maxima near the two enantiomeric structures, thus equal probability for finding each of the two enantiomers. In order to represent the experimental observation of localized enantiomers Hund considered the time dependent Schrödinger equation, Eq. (5), with the solutions for the time dependent wave functions (with time independent coefficients c_i) retaining just the two lowest terms in the sum (Eq. (7), corresponding to $\chi_+ = \varphi_1$ and $-\chi_- = \varphi_2$ and energies $E_+ = E_1$ and $E_- = E_2$). One obtains a time dependent probability density ($\Delta E_{1,2} = E_2 - E_1 = E_- - E_+$)

$$|\Psi(q,t)|^2 = \frac{1}{2}|\varphi_1 + \varphi_2 \exp(-2\pi \mathbf{i} \Delta E_{1,2} t/h)|^2 \tag{22}$$

when one takes equal coefficients $c_1 = c_2 = 1/\sqrt{2}$. This is an oscillatory function with a period

$$\tau' = h/\Delta E_\pm = h/(E_2 - E_1) \tag{23}$$

Inspection of the graphical representation of the wave functions on the left hand side in Fig. 7 shows that this moves from a function λ located near the left minimum at $t = 0$

$$\lambda = \frac{1}{\sqrt{2}}(\chi_1 - \chi_-) \tag{24}$$

to a function ϱ situated near the right hand minimum of the potential

$$\varrho = \frac{1}{\sqrt{2}}(\chi_+ + \chi_-) \tag{25}$$

in a time equal half the period

$$t_{\lambda \to \varrho} = \tau'/2 = \frac{h}{2\Delta E_\pm} \tag{26}$$

With these considerations Hund made two important observations: Firstly the 'reaction' from one enantiomer to the other can occur, although neither of the energies E_+ and E_- is sufficient to overcome the 'barrier maximum' $V(q_\mathrm{c})$, a process which would be completely impossible in classical mechanics. This was the discovery of the quantum mechanical 'tunnel effect', with numerous later applications in chemistry and physics (see [46, 117] for the history and reviews). Secondly, when estimating parameters for the effective masses and potentials for the 'inversion' (from R to S) in the case of the chiral substituted methane derivatives, Hund found millions to billions of years for the stereomutation times, thus explaining the apparent stability of CHFClBr, amino acids or sugars for example (see [118] for a critical discussion of the estimates, which does, however, not invalidate the conclusions).

The situation is quite different for the chiral molecules hydrogen-peroxide HOOH and the ammonia isotopomer, NHDT, which we have chosen here on purpose for illustration as Hund's description is effectively correct for these examples. While the simple one-dimensional model for stereomutation used by Hund and discussed by us above for illustration of the concept has become textbook material, only recently full-dimensional 'exact' solutions of the time independent and time dependent Schrödinger equation have become possible, as this requires the solution in a space of 6 internal (vibrational) coordinates $(q_1, q_2, \ldots, q_6)$ for the four atoms (nuclei) in these molecules and a potential hypersurface $V(q_1, q_2, \ldots, q_6)$ [94–96, 119–122] (and further dimensions if external rotation is included [96]). This results in a 6-dimensional wave function $\Psi(q_1, q_2, \ldots, q_6, t)$ and probability density $(|\Psi|^2)$. As a visualisation in a high dimensional space is not possible, one integrates over 5 coordinates $(q_1, \ldots, q_5)$ and represents the probability density as a function of one 'reaction coordinate' corresponding to the torsion angle τ in HOOH (still exact). Thereby one obtains a time dependent 'wave packet' as shown in Fig. 11 for HOOH

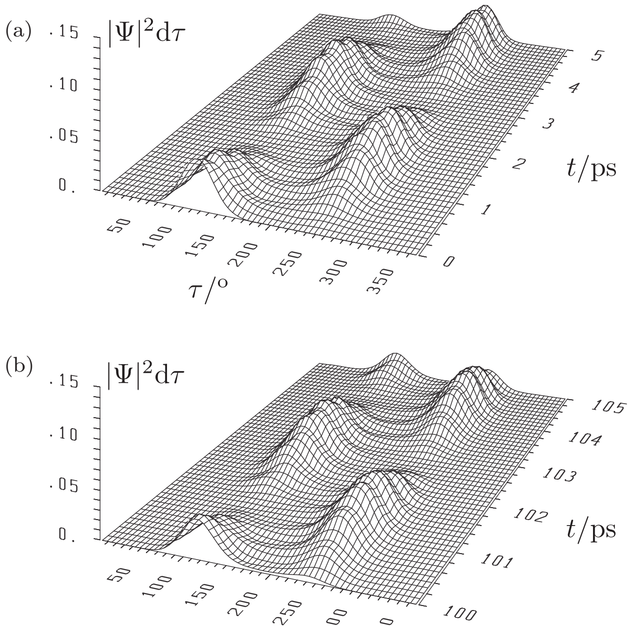


Fig. 11. Six-dimensional wave packet evolution for H_2O_2 in its lowest quantum states. $|\Psi|^2$ shows the time-dependent probability as a function of the torsional coordinate, where the probability density is integrated over all other coordinates. a) shows the time interval from 0 to 5 ps and b) the time interval from 100 to 105 ps with identical initial conditions at $t = 0$ as in a) [94, 95]. The migration of the wave packet from the left to the right corresponds to a change from one enantiomer of HOOH to the other in Fig. 9 with a transfer time according to Eq. (26) of about 1.5 ps (after [46]).

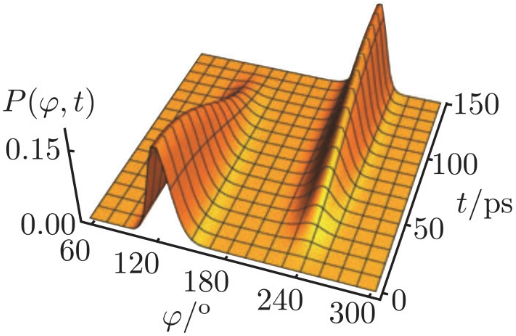


Fig. 12. Reduced probability density as a function of the inversion coordinate φ and time t for NHDT. The two enantiomeric structures correspond to $\varphi \cong 120^\circ$ and $\varphi \cong 240^\circ$, respectively, with $\varphi = 180^\circ$ corresponding to the planar geometry. The graphic shows reduced probability densities (probability densities integrated over all other coordinates) for the field-free isolated molecule (after [96]).

which moves from one enantiomeric structure at the left to the other enantiomeric at the right in about 1.5 ps [94, 95].

The corresponding result for the chiral ammonia isotopomer is shown in Fig. 12 [96]. Because of the short lifetime of the chiral, enantiomeric structures of HOOH or NHDT one may call such molecules 'transiently chiral'. The time dependence could be easily followed by observing time dependent optical activity or circular dichroism (also vibrational circular dichroism VCD or Raman optical activity, ROA), which will follow the wave packet motion in a straightforward manner.

The recent exact treatment for hydrogen-peroxide and ammonia isotopomers has also been extended to show various interesting effects such as mode selective tunneling stereomutation [95] or tunneling enhancement and inhibition by coherent radiative excitation [96]. We shall not pursue this in detail here but rather turn to the consequences of the asymmmetry arising from parity violation, illustrated on the right hand side of Fig. 7. Here one can distinguish two dynamical limiting cases. If the asymmetry due to parity violation ($\Delta_{\mathrm{pv}} E_{\mathrm{el}}$ in the scheme of Fig. 7) is small compared to the tunneling splitting $\Delta E_{\pm}$ in the symmetrical case

$$|\Delta_{\mathrm{pv}} E_{\mathrm{el}}| \ll |\Delta E_{\pm}| \tag{27}$$

then Hund's description as discussed above remains effectively valid. This is in fact the case for the examples HOOH and NHDT we have chosen here for illustration. The localization of the wave function is effectively due to the initial conditions only and corresponds to a symmetry breaking *de facto* ('fact like'). If on the other hand the asymmetry is large compared to the tunneling splitting

$$|\Delta_{\mathrm{pv}} E_{\mathrm{el}}| \gg |\Delta E_{\pm}| \tag{28}$$

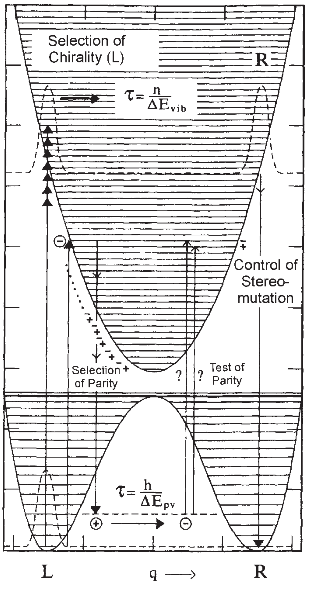
then the symmetry is broken *de lege* ('law like') and the stationary states of the time independent Schrödinger equation are in fact localized, in the example of Fig. 7

the ground state is located left λ at q_{L} and the first excited state on the right hand side ϱ at q_{R}. λ with E_λ and ϱ with E_ϱ are the eigenfunctions of 'infinite' lifetime, tunneling being almost completely suppressed. For a more detailed discussion of the concepts, the dynamics and including also a discussion of the classical concept 'spontaneous symmetry breaking' we refer to [23, 38–40, 45]. We anticipate here the results discussed below that in spite of the small magnitude of parity violation ($\Delta_{\mathrm{pv}}E_{\mathrm{el}} \approx 100\,\mathrm{aeV}$ in Fig. 7) for ordinary stable chiral molecules the case of *de lege* symmetry breaking applies, parity violation dominates completely over tunneling, very different from Hund's treatment of chiral molecules.

In this case the low energy eigenfunctions are localized (λ and ϱ) and do not have a well defined parity. The key idea for an experiment to study the extremely small values of $\Delta_{\mathrm{pv}}E$ follows the scheme of Fig. 4. One first prepares a state of well defined parity and then follows the slow time evolution of parity which arises from parity violation. Figure 13 shows how this can be done, in principle, following the proposal of Ref. 100. In the sequence of laser pulses shown in the figure one passes via an excited achiral state, which has spectroscopic energy eigenstates of essentially pure parity either + or − (− in the figure). With a second pulse using the spectroscopic selection rule for strong electric dipole transitions ($- \to +$) one prepares a state of well defined parity (+ in the figure). This state is not an eigenstate of energy and evolves in time following the equation

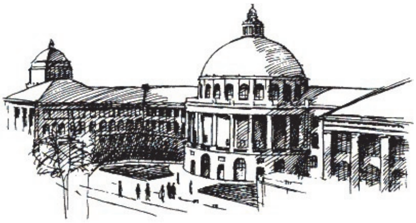
$$\Psi(t) = \frac{1}{\sqrt{2}} \exp\left(-2\pi \mathbf{i} E_\lambda t/h\right) \left[\lambda + \varrho \cdot \exp\left(-2\pi \mathbf{i} \Delta_{\mathrm{pv}} E t/h\right)\right] \tag{29}$$

The experimental approach on ΔE_{pv} (direct)



M. Quack, *Chem. Phys. Lett.* (1986)

The Zürich experiment on Time dependent parity



Ongoing experiments

Fig. 13. The Zurich experiment on time dependent parity (after Ref. 100).

The probabilities of parities as a function of time are given by Eq. (30)

$$1 - p_+(t) = p_-(t) = \sin^2\left(\pi \Delta_{\mathrm{pv}} E t / h\right) \tag{30}$$

If one measures this time dependence one can extract $\Delta_{\mathrm{pv}}E$. Details of spectroscopic experiments will be discussed in Sec. 4. At the time the proposal was made [100] it seemed almost impossible to actually carry out such experiments as most of the spectroscopic ground work was missing. Also it turned out that existing theories for predicting the effect were inadequate quantitatively. We shall in the following sections describe two steps in the long road towards such experiments. In Sec. 3 we discuss the development of quantitative theory followed by a description of current experiments in Sec. 4.

3. The quantitative theory of parity violation in chiral molecules

From 1925 onwards quantum mechanics provided a detailed theoretical understanding of how molecular structure and bonding arises [56–59, 71, 123–125] and modern electronic structure theory as summarised in reviews and text books would claim that this understanding is essentially complete [126–130], particularly when relativistic effects are included as well [131, 132]. Indeed, Dirac already in 1929 made the statement [124]:

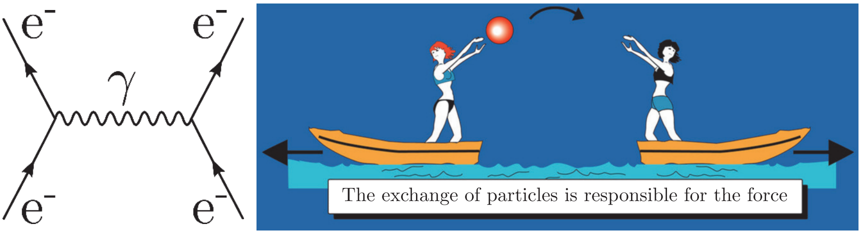
> '*The underlying physical laws for the mathematical theory of a large part of physics and the whole of chemistry are thus completely known and the difficulty is only that the exact application of these laws leads to equations much too complicated to be soluble. It therefore becomes desirable that approximate practical methods of applying quantum mechanics should be developed, which can lead to an explanation of complex atomic systems without too much computation.*'

This is one of the most frequently cited quotations in the quantum chemistry literature, even though often severely abbreviated [133]. However, the statement was incorrect, as the weak nuclear force introducing parity violation was completely unknown by that time, but turns out to have important consequences in stereochemistry, as we shall see.

The weak nuclear force was introduced by Enrico Fermi in his early theory of radioactive β-decay in 1934 [134]. Initially, there was no suspicion of a violation of space inversion symmetry by this force, until the suggestion by Lee and Yang [25] that assuming parity violation one could explain the so called $\Theta - \tau$ puzzle of elementary particle physics, which led to the dramatically fast discovery of parity violation in high energy physics [26–30]. This story is told in numerous places including historical articles and textbooks (see Refs. 31, 73, 135–137 for example). Figure 14 shows a pictorial representation of the current view of fundamental forces in the standard model of particle physics (SMPP) as shown on the website of a large accelerator [138]. We have modified this picture by adding the importance of the weak nuclear force for the stereochemistry of chiral molecules. We have also added the Feynman diagram for the example of the electromagnetic interaction of two electrons to illustrate, how action at a distance is viewed in the SMPP [139–141]

The Forces in Nature: Theory of electroweak quantum chemistry
Stereochemistry meets high energy physics

Type	**Intensity of Forces (Decreasing Order)**	**Particle Binding (Field Quantum)**	**Important in**
Strong Nuclear Force	~ 1	Gluons (no mass)	Atomic Nucleus
Electro-Magnetic Force	$\sim 10^{-3}$	Photons (no mass)	Atoms and Molecules
Weak Nuclear Force	$\sim 10^{-5}$	Bosons Z, W^+, W^- (heavy)	Radioactive β-Decay, Neutrino induced dec. **Chiral Molecules**
Gravitation	$\sim 10^{-38}$	Gravitons (?)	Sun and Planets etc.



Piazza Armerina CERN AC_Z04_V25/B/1992

Fig. 14. Forces in the standard model of particle physics (SMPP) and important effects. This is taken from the CERN website Ref. [138], but the importance of the weak interaction for chiral molecules has been added here from our work (modified after [40], in turn, adapted from Ref. [138], Public Domain. We note that, while not referred to in Ref. [138], the motif of the lightly dressed ladies throwing balls can be found in a mosaic at Piazza Armerina. Sicily, from the 4th century AD). We also added the Feynman diagram to the left representing the electromagnetic interaction between two electrons (e^-) via the photon (γ) as field quantum (see also [139]).

(the diagrams are also sometimes called Stueckelberg diagrams, e.g. by Gell-Mann, or Feynman-Stueckelberg diagrams due to earlier contributions of Stueckelberg to the developments [142–147]). According to this view, the electromagnetic force, which is included in the 'Schrödinger-Dirac' like ordinary quantum chemistry, leads to the Coulomb repulsion, say, between two electrons by means of photons as field particles. In the picture the two electrons are compared to the ladies on two boats throwing a ball. If we do not see the exchange of the ball, we will only observe the accelerated motion of the boats resulting from the transfer of momentum in throwing the ball. We could interpret this motion as resulting from a repulsive 'force' between the two ladies on the boats. Similarly, we interpret the motion of the electrons resulting from 'throwing photons as field particles' as arising from the Coulomb law which forms the basis of the Hamiltonian in ordinary quantum chemistry. Different from the simple quasiclassical analogy, the Feynman diagram, which almost looks like representing such a picture, can be translated into quantitative mathematical equations, which then form the basis of a quantitative theoretical treatment of the interactions and dynamics [148]. The Coulomb force with the $1/r$ potential energy law is of long range. The other fundamental forces arise similarly, but with other field particles. The strong force with very short range (0.1 to 1 fm) mediated by the gluons is important in nuclear physics but has only indirect influence in chemistry by providing the structures of the nuclei, which enter as parameters in chemistry, but there is otherwise normally no need to retain the strong force explicitly in chemistry. The weak force, on the other hand, is mediated by the $W^{\pm}$ and Z^0 bosons of very high mass (86.316 and 97.894 Dalton, of the order of the mass of a Rb to Mo nucleus) and short lifetime (0.26 yoctoseconds = $0.26 \cdot 10^{-24}$ s, Ref. 47). This force is weak and of short range (< 0.1 fm) and one might think that, similar to the even weaker gravitational force (mediated by the still hypothetical graviton of spin 2), it should not contribute significantly to the forces between the particles in molecules (nuclei and electrons). Indeed, the weak force, because of its short range, becomes effective in atoms and molecules, when the electrons penetrate the nucleus and then it leads only to a very small perturbation on the molecular dynamics, which ordinarily might be neglected completely. However, in fact the weak force leads to a fundamental change as it has a different symmetry, violating space inversion symmetry, which is *exactly* valid for the strong and electromagnetic interactions (also gravitational interactions) according to present knowledge. When including the parity violating weak interaction, qualitative theory therefore tells us already that the ground state energies (and other properties) of enantiomers of chiral molecules will be different. The question remains then just how different the energies will be quantitatively. We shall not go into technical details here of the formulation of the quantitative theory of electroweak quantum chemistry (a term coined by us in [101, 149]). However, some brief remarks may be in order concerning the development and current status of the theory of parity violation in chiral molecules, which has been reviewed in detail elsewhere [23, 40, 112, 150, 151] (see also Refs. 22, 42, 101, 149, 152). The history of this theory can be broadly summarized in three phases.

In a first phase, after the discovery of parity violation in nuclear and high energy physics [25–30] in 1957, qualitative suggestions were made concerning the role of parity violation in chiral molecules, with estimates which were often wrong by many orders of magnitude (in the period of about 1960–1980 [153–155], see also the reviews in [22, 23, 38, 40] for many further references). In a second phase, attempts towards a quantitative theory started in about 1980, based on earlier work on the theory for atoms [156, 157], extended approximately to molecules by Hegström, Rein and Sandars [158], Mason and Tranter [159] and others [160, 161] (see also the further citations in [23, 38, 40, 42]). It turned out, however, that these approaches were quite inadequate quantitatively.

A third phase started when in 1993–1995 we carefully reinvestigated in relation to our experimental project [38, 100] also the theory, rederiving it from its foundations in the standard model and critically analysing the steps towards 'electroweak quantum chemistry' [101, 102, 149]. Indeed, we found values for the parity violating energy differences $\Delta_{\mathrm{pv}}E$ in typical chiral 'benchmark' molecules often by one to two orders of magnitude larger as compared to previous results. In spite of some initial scepticism, which some audiences expressed towards the two-order of magnitude increase reported by us also in our lectures at the time (also in [162], for example), our discovery of the new, much larger values triggered further work and were subsequently confirmed by quite a few other theory groups [163–166] (see [23, 40, 42, 112, 150] for further references). Today there seems to be general agreement on the new orders of magnitude from a number of quite different approaches (see for instance the recent summary in [152]), although the current results still scatter within about a factor of 2, which has various more technical reasons not to be discussed in detail here.

Figure 15 illustrates the big quantitative jump discovered in our theoretical work in the mid 1990s, which stimulated much further theoretical work (and also experimental efforts). We summarize here the main steps in the theoretical development, which is described 'from scratch' up to practically useful equations in Ref. [101] (see also the review in Ref. [150], in particular, containing also some historical remarks). The starting point are the fully relativistic equations from the SMPP describing electron-neutron, electron-proton and electron-electron interactions in the order of their importance. In principle, one starts with electron-quark interactions at a more fundamental level (see [150]). One takes the low energy semirelativistic limit and then also neglects the electron-electron parity violating interactions which can be considered to be a smaller contribution only. For not too heavy nuclei of interest in simple inorganic and organic molecules (and also biomolecules) appropriate for fundamental studies one can use to a good approximation the Breit-Pauli form of the semirelativistic one- and two-electron spin-orbit interaction. For molecules involving heavy elements one can use as an alternative the Dirac Fock theory given

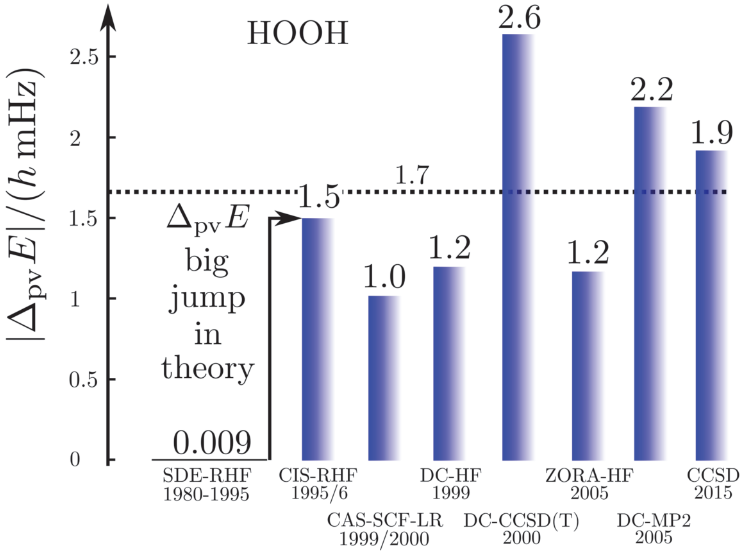


Fig. 15. Graphical representation of the 'big jump' in theory occurring in 1995 (after Ref. [42], values of the parity violating energy differences $\Delta_{\rm pv}E$ are shown for the benchmark molecule hydrogen-peroxide H_2O_2, note the extremely small unit for energy $\Delta_{\rm pv}E/h$ in millihertz).

by Laerdahl and Schwerdtfeger in 1999 [164] and related approaches [166, 167], see also the reviews [112, 150, 151, 168]. Finally, one can represent the nucleus by a point like object with the electric charge $-Z_\mathrm{A}\, e$ (Z_A = number of protons) and an electroweak charge (neglecting also radiative corrections)

$$Q_\mathrm{A} = [1 - 4\sin^2(\Theta_\mathrm{W})]Z_\mathrm{A} - N_\mathrm{A} \tag{31}$$

with the number of neutrons N_A. This last approximation can be rather easily improved upon by considering the actual shape of the nucleus with its distribution of neutrons and protons [169] from the theory of nuclear structure, where we note here the interesting sensitivity of parity violating effects upon the neutron distribution, indeed, with the parameter $[1 - 4\sin^2(\Theta_\mathrm{W})] = 0.0724$ [60]. We note that the value of the Weinberg parameter $\sin^2\Theta_\mathrm{W}$ (or weak mixing parameter) depends on the scheme used and the momentum transfer. At every step in these approximations one can, in principle, check these by the inclusion of the neglected effects, and none of the approximations is fundamental, although considerable computational effort may be necessary to improve upon them. The convergence of current theories as described by Fig. 15 would indicate that at least no 'trivial' effects have been overlooked, although tests by experiment seem advisable after past experience. We can add here that precision experiments on molecular parity violation can contribute in general ways to fundamental aspects of physics as well. If the nuclear structure is well known, as is the case for the lighter nuclei up to Argon at least, then precision experiments can contribute to a better understanding of the weak mixing parameter according to Eq. (31). On the other hand, for heavier nuclei, where the structure is less well known, precision experiment on parity violation could provide significant information on the neutron distribution in the nucleus, whereas many other experiments are most sensitive to the proton distribution.

At this point it may also be of interest to refer to the extensive theoretical and experimental work available for atomic parity violation (see [156, 157, 170–176] for a small selection). While quite a number of successful spectroscopic observations of parity violation exist for atoms, these are restricted to very heavy atoms and this restriction remains probably valid for the foreseeable future. Because of uncertainties in both electronic and nuclear structure for heavy atoms, a quantitative theoretical analysis leads to relatively large uncertainties with respect to an analysis of fundamental parameters in the theory (such as $\sin^2(\Theta_\mathrm{W})$). A similar restriction is true also for recent efforts on studies of parity violation in diatomic molecules (so far unsuccessful, in contrast to atoms). We shall not discuss these further here and refer to the recent review by Berger and Stohner [168] which has a focus on atoms and diatomic molecules.

In contrast, as we shall see below, certain spectroscopic studies on parity violation in chiral molecules have the promise to be successful in molecules involving only the lighter elements. They are thus of interest also in terms of fundamental physics. Furthermore, studies of parity violation in chiral molecules provide a direct link to effects that may be important for biochemistry and the evolution of biomolecular homochirality, which provides a further fundamental motivation for such studies. The scatter in the current results for $\Delta_{\text{pv}}E$ of the benchmark molecule HOOH should not be taken as an indication that accurate calculations are not possible: Indeed, the scatter is in part due to the fact that a somewhat hypothetical value of $\Delta_{\text{pv}}E^{\text{el}}$ is computed and to secondary effects. For molecules, where $\Delta_{\text{pv}}E_0$ corresponds to a measurable quantity as a ground state energy difference, this can be accurately calculated, if also vibrational effects are taken into account (see discussion in [23, 55]; we use here the symbol $\Delta_{\text{pv}}E_0$, when we wish to refer explicitly to the overall ground state, rotational — vibrational — electronic, perhaps also hyperfine).

Without going into any detail of the theory for chiral molecules, we shall provide here a simplified summary of some of the main aspects and a few exemplary results. An instructive approximate form for the parity violating potential in chiral molecules is given by Eq. (32) from perturbation theory

$$E_{\text{pv}} = 2\,Re\left\{\sum_m \frac{\langle\psi_0|\hat{H}_{\text{pv}}^{\text{e}-\text{nucl.}}|\psi_m\rangle\langle\psi_m|\hat{H}_{\text{SO}}|\psi_0\rangle}{E_m - E_0}\right\} \tag{32}$$

where ψ_0 would be the electronic wave function of the ground state, say, a singlet state and ψ_m is some excited (triplet) state. The sum extends over many excited electronic states for convergence. $\hat{H}_{\text{SO}}$ is the spin-orbit Hamiltonian. The parity violating Hamiltonian $\hat{H}_{\text{pv}}$ has a dominant term

$$\hat{H}_{\text{pv},1}^{\text{e}-\text{nucl.}} = \frac{\pi G_{\text{F}}}{m_e hc\sqrt{2}} \sum_{j=1}^{n}\sum_{\text{A}=1}^{N} Q_{\text{A}}\left\{\hat{p_j}\cdot\hat{s}_j, \delta^3(\vec{r_j}-\vec{r_{\text{A}}})\right\}_+ \tag{33}$$

Here we use SI units with common symbols for the fundamental constants [60] and in particular the Fermi constant

$$G_{\text{F}} = 1.4358510(8)\cdot 10^{-62}\,\text{Jm}^3 \tag{34}$$

One notes the small value for G_{F}. The sums extend over all electrons (n) and all nuclei (N) in the molecule. $\{,\}_+$ is the symbol for the anticommutator and $\hat{p}_j$ is the momentum and $\hat{s}_j$ the spin operator for the j^{th}-electron. The Dirac-delta function $\delta(\vec{r_j}-\vec{r}_{\text{A}})$ vanishes at all values except when $\vec{r_j} = \vec{r}_{\text{A}}$ in the point nucleus approximation (see above). This part of the parity violating Hamiltonian is sufficient when discussing properties independent of nuclear spin. When nuclear spin I_{A} is to be considered as for hyperfine structure or for NMR experiments one has to include a nuclear spin dependent term

$$\begin{aligned}\hat{H}_{\text{pv},2}^{\text{e}-\text{nucl.}} = \frac{\pi G_{\text{F}}}{m_e hc\sqrt{2}} \sum_{j=1}^{n}\Bigg[&\sum_{\text{A}=1}^{N}(\lambda_{\text{A}})(1-4\sin^2\Theta_{\text{W}})\left\{\hat{\mathbf{p}}_j\hat{\mathbf{I}}_{\text{A}}, \delta^3(\vec{r_j}-\vec{r}_{\text{A}})\right\}_+ \\ &+ (2\mathbf{i}\lambda_{\text{A}})(1-4\sin^2\Theta_{\text{W}})(\hat{\mathbf{s}}_{\mathbf{j}}\times\hat{\mathbf{I}}_{\mathbf{A}})\left[\hat{\mathbf{p}}_j, \delta^3(\vec{r_j}-\vec{r}_{\text{A}})\right]_-\Bigg]\end{aligned} \tag{35}$$

Here again $\{,\}_+$ is the anticommutator and $[,]_-$ is the commutator. We note that because of Eq. (31) neutrons provide the dominant contribution to the weak charge of the nucleus (except for the case of the proton, of course). We can also note that while NMR spectroscopy is among the most powerful spectroscopic methods [177] and has been suggested for the study of parity violation in chiral molecules [178], conclusive results are to be expected only for such experiments, if carried out in molecular beams as discussed in Refs. 23, 39, as they were done at the very start of NMR spectroscopy [179, 180]. We note furthermore, that as the neutron number is different for different isotopes, parity violation introduces a fundamentally new isotope effect arising from the weak nuclear charge Q_{A}: Isotopic chirality is important for parity violation as pointed out in Refs. 23, 38 and calculated quantitatively in Ref. [181]. We should also mention, that Eq. (32), which we gave here, because it leads to some instructive insight on the structure of the potential, in actual calculations this has slow convergence of the sum, when carried out numerically in this way [101, 149]. In practice one uses response theory equivalent to Eq. (32) as established through propagator methods (see Refs. 23, 40, 46, 102 for discussions). In contrast to atoms, the parity violating potential E_{pv} in polyatomic (chiral) molecules depends on $S = 3N - 6$ internal coordinates describing the structure of the molecule. Similar to the ordinary electronic potential energy of the molecule it is a potential hypersurface in an S-dimensional space. As chiral molecules necessarily have at least 4 atoms, this is an at least 6-dimensional space (for the examples H_2O_2 or NHDT the space would be just 6-dimensional). We can thus write with some general internal coordinates more explicitly

$$E_{\mathrm{pv}} = E_{\mathrm{pv}}(q_1, q_2, q_3, ..., q_s) \tag{36}$$

This potential is antisymmetric with respect to the operation of space inversion $\hat{P}$ or $\hat{\mathrm{E}}^*$, we can thus write with a symbolic notation for the inverted coordinates $\bar{q}_i$:

$$\hat{\mathrm{E}}^* E_{\mathrm{pv\,R}}(q_1, q_2, q_3, \ldots, q_s) = E_{\mathrm{pv\,S}}(\bar{q}_1, \bar{q}_2, \bar{q}_3, \ldots, \bar{q}_s) = -E_{\mathrm{pv\,R}}(q_1, q_2, q_3, \ldots, q_s) \tag{37}$$

We can define a parity violating energy difference

$$\Delta_{\mathrm{pv}} E(q_1, q_2, q_3, \ldots, q_s) = E_{\mathrm{pv\,R}}(q_1, q_2, q_3, \ldots, q_s) - E_{\mathrm{pv\,S}}(\bar{q}_1, \bar{q}_2, \bar{q}_3, \ldots, \bar{q}_s) \tag{38}$$

Here we omit the extra index “el” for simplicity. The absolute values of these parity violating energy differences for given structures are very small, on the order of sub-feV typically for molecules composed of lighter atoms only. The sign of $\Delta_{\mathrm{pv}} E$ depends on the structure and we note that for some well-defined convention (say R and S in the CIP convention or P and M for axially chiral molecules or D and L in another convention), $\Delta_{\mathrm{pv}} E$ may change sign even within a given domain (say all R). We denote by $E_{\mathrm{pv\,R}}$ or $E_{\mathrm{pv\,S}}$ that the potential refers to an R or S structure in the given convention.

This is illustrated for the example ClSSCl in Fig. 16, where the potentials are shown as a function of just one coordinate, the torsional angle τ as indicated. The parity violating potentials shown in color are antisymmetric with respect to inversion at the point $\tau = 180^{\circ}$, where they are zero by symmetry. On the other hand one sees a sign change also in the range of some chiral geometries with an ‘accidental’ value $E_{\mathrm{pv}} = 0$ at chiral geometries of about $\tau \approx 80^{\circ}$ and $\tau \approx 280^{\circ}$. Nevertheless

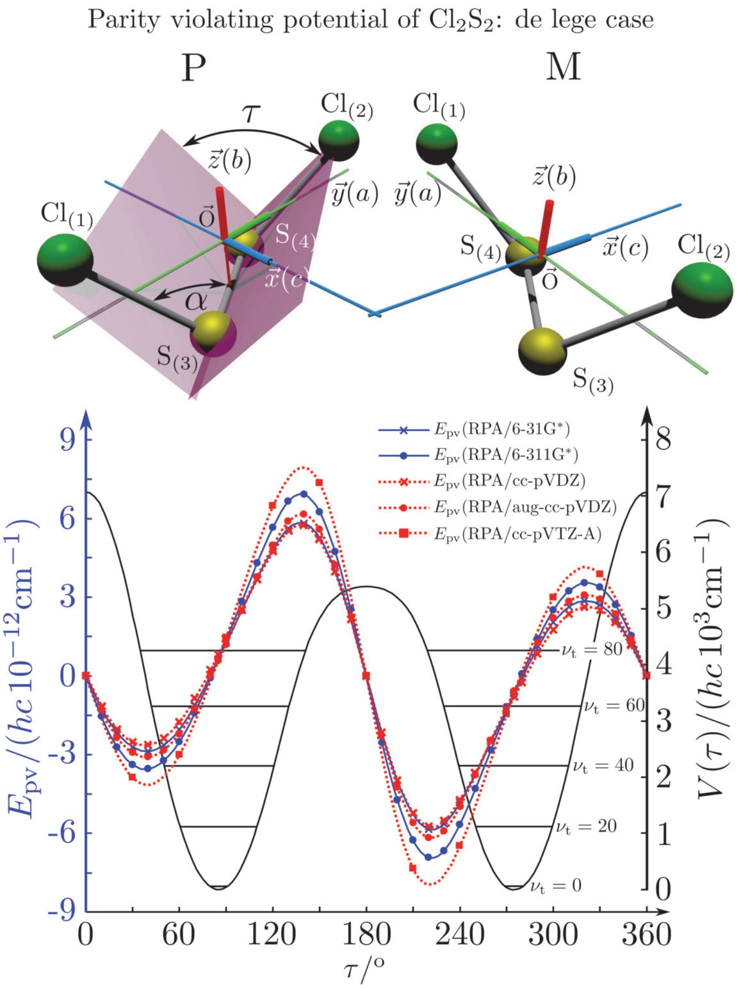


Fig. 16. Calculated torsional potential (full line, right ordinate scale) and parity-violating potential (left ordinate scale, lines with various symbols for various approximations in the electroweak quantum chemistry [97]) for ClSSCl. The equilibrium structure and the definition of the torsional angle τ are shown in the upper part of the figure [99] (after Ref. [97]).

it is true that two mirror image structures have exactly the same absolute value but opposite sign for E_{pv} (but possibly being zero), as the potential is strictly antisymmetric. On the other hand, the Born Oppenheimer electronic potentials shown by the full black line in Fig. 16 are strictly symmetric with respect to inversion at $\tau = 180^{\mathrm{o}}$. This result is true also going beyond the Born-Oppenheimer approximation at higher levels of approximation and in fact the symmetry remains true for the exact electromagnetic Hamiltonian at all orders of precision: The difference of energies between mirror image (space inverted) structures is exactly zero by symmetry as long as only strong and electromagnetic interactions are included. We note that in [182] higher dimensional parity violating potential hypersurfaces are discussed and some graphical representations for 2-dimensional surfaces are shown. As discussed in Sec. 2 with Eqs. (27) and (28) one must discuss the relative magnitude of the parity violating potentials in relation to tunneling processes connecting the two enantiomers. Only when parity violation dominates over tunneling, Eq. (28), one will have localized wave functions and a measurable ground state energy difference $\Delta_{\mathrm{pv}}E_0$ between the enantiomers. We have systematically studied this for the series of hydrogen isotopomers XYYX, i.e. for the chalcogenic Y and X=H,D,T including also mixed compounds (i.e. with X,X$'$ different and Y,Y$'$ different) and further compounds ZYYZ with other elements Z and further compounds and this has been reviewed recently [46]. It turns out that for the example HOOH the tunneling splittings $|\Delta E_{\pm}|$ for the symmetrical potentials are much larger than the $|\Delta_{\mathrm{pv}}E|$. Thus in HOOH one does not find a measurable parity violating ground state difference $|\Delta_{\mathrm{pv}}E_0|$, the ground state is delocalized and has almost pure parity, as also excited rovibrational-tunneling states, as discussed in Sec. 2. For the higher elements in the series the tunneling splittings become comparable to $|\Delta_{\mathrm{pv}}E_{\mathrm{el}}|$. TSeSeT being the first example where parity violation dominates, and for the tellurium and polonium compounds parity violation dominates already for the deuterated compounds, thus these molecules might, in principle, be useful for measurements of $\Delta_{\mathrm{pv}}E_0$ disregarding other problems arising from chemical properties and radioactivity.

$\Delta_{\mathrm{pv}}E$ roughly scales with the 5th power of the heaviest nuclei in the molecule as suggested by an equation originally given by Zel'dovich [183, 184] and complemented in [23] by a geometry dependent factor f_{geo} (for Zel'dovich $f_{\mathrm{geo}} = 1$)

$$\frac{\Delta_{\mathrm{pv}}E}{h} = f_{\mathrm{geo}}(q_1, q_2, q_3, ...q_s) \cdot 10^4 \cdot \left(\frac{Z_{\mathrm{eff}}}{100}\right)^5 \ \mathrm{Hz} \qquad (39)$$

This would provide a simple estimate, if one takes some weighted average over the charge numbers of the nuclei in the molecule (in the simplest case the weighted average of the two heaviest nuclei [23]). The simple scaling with Z^5 is suggested by the form of the operators, the effect of spin orbit coupling and of the weak nuclear charges Q_{A} taking the simple approximation that the number of neutrons is roughly proportional to Z as well. The problem in such scaling formulae arises from the complicated form of $f_{\mathrm{geo}}(q_1, q_2, q_3, ...q_s)$ and a critical discussion can be found in Ref. [182]. An obvious way to find molecules with smaller tunneling splittings is to use compounds ZYYZ (or ZYYX etc.) with heavier Z-atoms and interesting examples are ClOOCl [103, 185, 186] and ClSSCl [97, 99]. Figure 16 shows the torsional potential and the parity violating potential as a function of the torsional angle (with scales on the ordinate axes being different by 15 orders of magnitude as shown).

ClSSCl is an example where the tunneling splitting was shown to be at least 40 orders of magnitude smaller then the parity violating potentials [97] as recently reconfirmed [187]. Thus in this molecule, the ground states of each enantiomer are clearly localized at the chiral structures and one can significantly measure a ground state energy difference $\Delta_{\mathrm{pv}}E_0$ between the enantiomers of this molecule. This measurable energy difference for the ground state (or excited rovibrational states possibly including hyperfine substructures) can be calculated by the expectation values for the corresponding rovibronic (possibly nuclear spin hyperfine) state $\varphi_{\mathrm{evr}}^{(k)}$:

$$\Delta_{\mathrm{pv}}E^{(k)} = \langle \varphi_{\mathrm{evr}}^{(k)} | E_{\mathrm{pv\,R}}(q_1, \ldots, q_s) | \varphi_{\mathrm{evr}}^{(k)} \rangle - \langle \varphi_{\mathrm{evr}}^{(k)} | E_{\mathrm{pv\,S}}(\bar{q}_1, \ldots, \bar{q}_s) | \varphi_{\mathrm{evr}}^{(k)} \rangle \tag{40}$$

The ground state energy difference $\Delta_{\mathrm{pv}}E_0$ is a special case with $k = 0$. Sometimes the $\Delta_{\mathrm{pv}}E_0$ can be approximated by taking the values of the parity violating potentials at the equilibrium geometries $\Delta_{\mathrm{pv}}E_{\mathrm{el}}(q_e)$. For ClSSCl, for example, one finds $\Delta_{\mathrm{pv}}E_0 = hc \cdot 1.35 \cdot 10^{-12}\,\mathrm{cm}^{-1}$ and $\Delta_{\mathrm{pv}}E_{\mathrm{el}}(q_e) = hc \cdot 1.29 \cdot 10^{-12}\,\mathrm{cm}^{-1}$, Ref. 97, where the vibrational averaging was restricted to the torsional coordinate to obtain an estimate for the uncertainties introduced by vibrational averaging (see also Ref. 55).

4. Towards spectroscopic experiments

4.1. *Developing experimental concepts and spectroscopic techniques for the study of parity violation in chiral molecules*

Successful spectroscopic experiments promise great progress in fundamental aspects of molecular and biomolecular stereochemistry and possibly also concerning precision experiments on parameters of the standard model of particle physics (SMPP). At the same time such experiments also present a major challenge because of the small magnitude of the predicted effects, and there are no ‘low hanging fruits’ to be harvested, even though the high hanging fruits may be of particularly good taste. As of today there seem to be only two reasonably advanced efforts world wide, one in Zürich which started with first publications from 1986 [100] onwards and one in Paris, starting with first publications in 1999 [188]. The two projects have been reviewed for example in Refs. [23, 39, 45, 46, 112] and [189, 190]. Other groups have expressed interest in developing experimental projects (e.g. [191]), but there does not seem to be any concrete published record on progress in any of these. There have been proposals on a variety of experimental concepts on how to address parity violation in chiral molecules and we have summarized these before [23, 39]. None of these other schemes seems to be particularly promising or easier than the schemes used in current projects, but one should certainly also consider these and further possibilities [277]. Here we shall discuss only the two different concepts for the currently ongoing projects. Figure 17 shows a graphical survey of the historical development, from which one can get an overview over these really long term efforts.

The different concepts can be understood with the energy level scheme shown in Fig. 3. In a scheme originally proposed by Letokhov in 1975 [192, 200] one attempts to measure a difference in the high resolution spectra of the separate enantiomers S and R, which may for a particular transition have the frequency ν_{S} and ν_{R} in the different enantiomers. As one can see from the scheme in Fig. 3 this corresponds

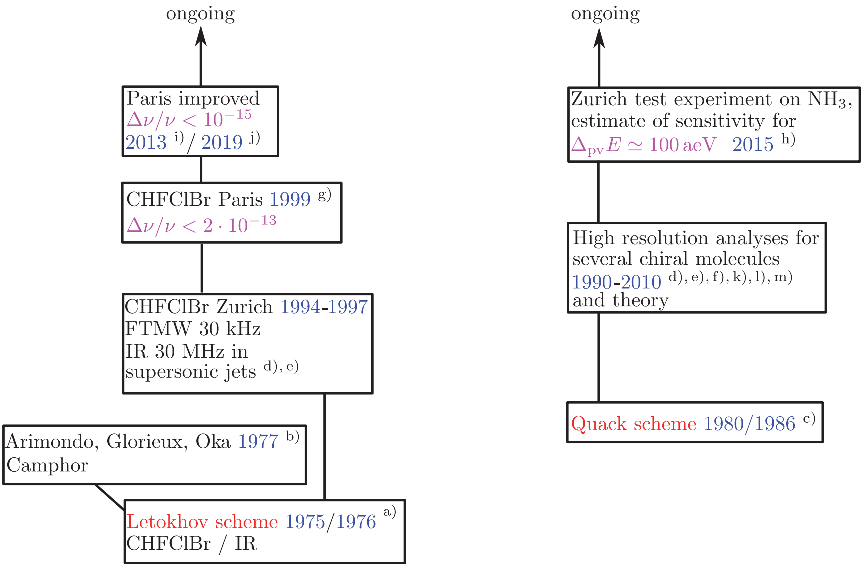


Fig. 17. Graphical survey of the historical development of the two currently pursued experimental concepts (with a) Ref. 192, b) Ref. 193, c) Ref. 100, d) Ref. 194, e) Ref. 195, f) Ref. 196, g) Ref. 188, h) Ref. 104, i) Ref. 189, j) Ref. 190), k) Ref. 197, l) Ref. 198, m) Ref. 199.

to a difference of parity violating energy differences $\Delta_{\rm pv}E$ in two corresponding molecular levels

$$\Delta_{\rm pv}E^* - \Delta_{\rm pv}E = h(\nu_{\rm R} - \nu_{\rm S}) \tag{41}$$

The group of Letokhov has already tried to see a corresponding splitting of lines in infrared spectra of CHFClBr in a racemic mixture [200] measuring at sub-Doppler resolution of about $\Delta\nu/\nu \simeq 10^{-8}$, which is almost ten orders of magnitude away from the effect as calculated later [54]. Shortly thereafter Arimondo, Glorieux and Oka did sub-Doppler Lamb-Dip spectroscopy on camphor with separated enantiomers, with about a similar precision [193]. Again, the effect was calculated later to be much smaller [201] for camphor as well. We have in Zurich followed Letokhov's scheme in parallel to our scheme, achieving high resolution analyses with hyperfine structure analysis of microwave and rovibrational infrared of CHFClBr [194, 195] spectra of supersonic jets. This work identified coincidences with CO_2 laser lines and came to the conclusion, that with ultrahigh resolution sub-Doppler spectroscopy using these or related coincidences one might approach resolutions sufficient to identify parity violating effects [195]. Such experiments were subsequently actually carried out in Paris [188] achieving $\Delta\nu/\nu \simeq 2 \cdot 10^{-13}$ still several orders of magnitude away from the theoretically predicted effects [54]. With subsequent improvements reviewed in [189, 190], the currently ongoing experiments appear to be promising for molecules involving very heavy elements, where the parity violating effects are relatively large. So far, no experiment along these lines has been successful, however.

In the other concept proposed by us in 1986 [100], actually informally reported earlier on a few occasions between 1977 and 1986 already (see [47] and references cited therein), one makes use of an 'achiral' excited molecular energy level of well defined parity which has radiative electric dipole transition moments connecting to both enantiomers (see Figs. 3 and 18). Using such a level, one can prepare a coherent superposition of well defined parity in the ground state and follow the time evolution of parity due to parity violation (see Sec. 2). From this, one obtains $\Delta_{\text{pv}}E$ directly and separately (one could also measure some $\Delta_{\text{pv}}E^*$ separately, of course [23]). This scheme can also be carried out in frequency resolved experiments, when $\Delta_{\text{pv}}E$ can be isolated as a spectroscopic 'combination difference' [38]. We shall discuss now properties for the time dependent scheme in more detail, as this has some advantages [42]:

(i) the requirements for spectral resolution are less severe, being sufficient for state selection,
(ii) there is no need to prepare pure enantiomers, the experiment works for racemic mixtures as well as for separate enantiomers,
(iii) one measures the parity violating energy difference between the corresponding levels of the enantiomers directly and separately for every pair of levels instead of only a 'difference of differences', as given by Eq. (41),
(iv) the technique has been demonstrated to be able to measure smaller absolute values of the parity violating energy difference than by the other scheme, thus allowing one to study molecules involving only light nuclei.

4.2. *Towards a measurement of $\Delta_{\text{pv}}E$ and a test of sensitivity with an achiral molecule*

Our approach in Zurich [100] can be illustrated with the scheme outlined in Fig. 18. It uses the idea that either one may have a planar excited electronic state, where the rovibronic levels have essentially well defined parity or else one has a modest barrier for stereomutation in the ground state, where one can thus reach by vibrational excitation with infrared lasers levels near to or above the barrier, where they can have large tunneling splittings and thus satisfy the condition in Eq. (27), guaranteeing that they have essentially well defined parity, a typical tunneling switching situation [186]. Then one can carry out an experiment following the schemes in Fig. 4 and Fig. 19. One first prepares with a sequence of two laser pulses a state of well defined parity at low energy, where the inequality Eq. (28) applies. One can use rapid adiabatic passage (RAP) in a molecular beam experiment [104] or chirped laser pulses [103] or also stimulated Raman adiabatic passage (STIRAP) [105]. This prepared parity state is time dependent and evolves under parity violation according to Eqs. (5), (29) and (30) (in the two state approximation).

This is a periodic time evolution with a period on the order of a second, depending on the value of $\Delta_{\text{pv}}E$. In the molecular beam setup shown in Fig. 19 the evolution time after preparation will be on the order of milliseconds with typical

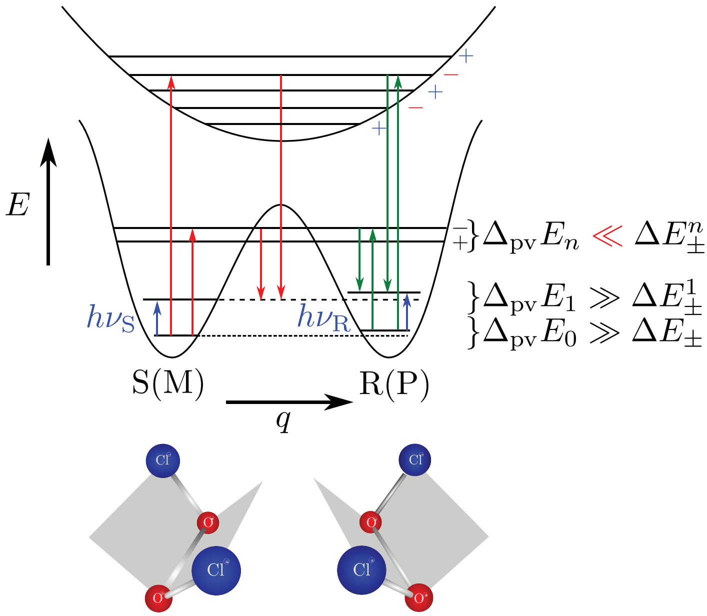


Fig. 18. Enantiomers of chiral molecules of the general type X-Y-Y-X and scheme for the experiment to measure $\Delta_{\text{pv}}E$ (red arrows for time-dependent experiment) and $\Delta_{\text{pv}}\nu := \nu_{\text{S}} - \nu_{\text{R}}$ (blue arrows). The combination of selected red and green arrows in the scheme leads to a measurement of $\Delta_{\text{pv}}E$ in the frequency domain. The excited state of well defined parity (plus or minus signs) can be in an electronically excited state or in an excited vibrational-tunneling state as shown in Ref. [186]. The red arrow in absorption corresponds to a transition between an S and a negative parity level (energy $h\nu_{\text{S}-}$). The green arrow in absorption corresponds to a transition between an R and a negative parity level (energy $h\nu_{\text{R}-}$). The difference is $h\nu_{\text{R}-} - h\nu_{\text{S}-} = \Delta_{\text{pv}}E_0$. The energy difference between the two blue absorption lines within R and S, $h\nu_{\text{S}} - h\nu_{\text{R}} = \Delta_{\text{pv}}E_0 - \Delta_{\text{pv}}E_1$, is the difference of parity violating energy differences (modified after [48, 112] and [186]).

molecular speeds and a flight path on the order of 1 m. One can use the approximation $\sin^2 x \approx x^2$ for small values of the argument resulting in

$$1 - p_+(t) = p_-(t) \simeq \pi^2 \Delta_{\text{pv}} E^2 t^2 / h^2 \tag{42}$$

This change in the populations can be observed spectroscopically because the rovibronic spectra of the parity isomers differ, as shown in Fig. 20. When one has a full assignment of the rovibronic spectrum of the R or S enantiomer (or a racemic mixture) one can label each line by a parity symbol '+' or '-', depending upon whether it connects to a positive or negative parity of the upper level in the transition, all lines being allowed in the spectrum for the ordinary chiral molecule (R or S or racemic mixture) of the upper part in Fig. 20. After preparation of a 'negative parity isomer' in the preparation steps only the blue lines marked with a + will appear due to electric dipole selection rules. As the character of the prepared state changes parity in time following Eqs. (30) and (42), this can be probed by detecting transitions at frequencies corresponding to the red lines marked '-'. This

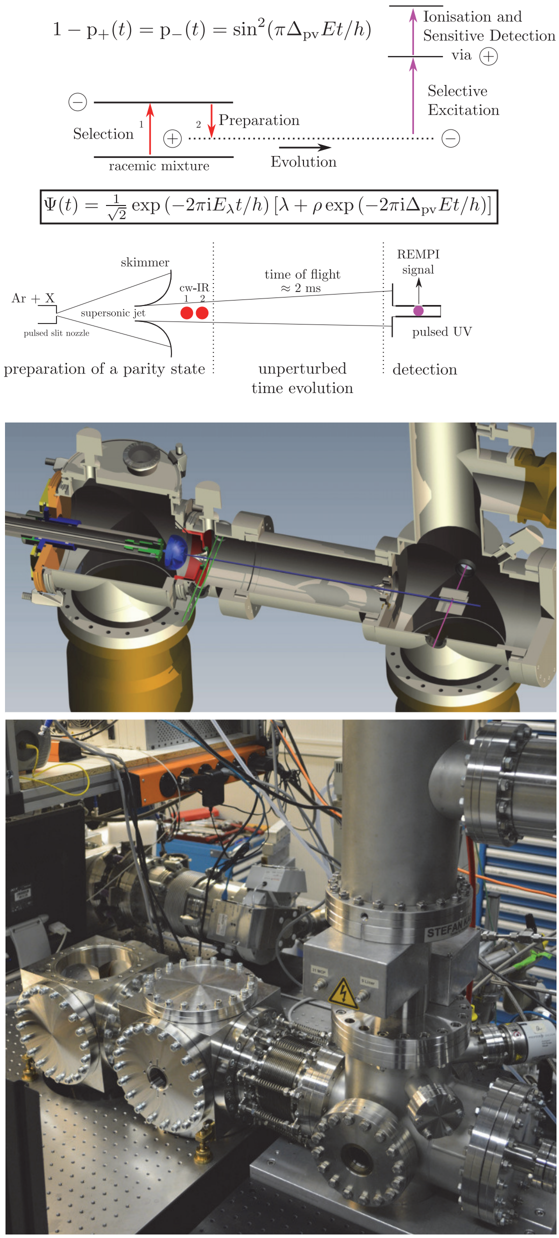


Fig. 19. Experimental molecular beam setup showing the three laser beams of the three steps (top part, scheme, middle part, modified after [104] and below a photograph of the time-of-flight part of the actual setup). We note that the laser systems used in the experiment need actually much more space than this 'core' part of the experiment. In the back one can also see a part of the setup for comb based high-resolution cavity-ring down spectroscopy of molecules in a supersonic jet expansion [202].

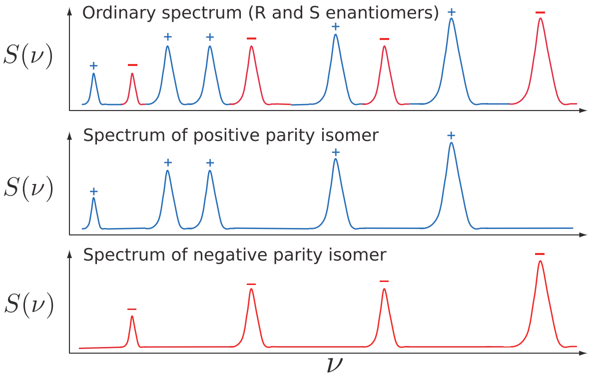


Fig. 20. Schematic illustration of the spectral changes in the superposition experiment (modified after [45, 112]).

detection can be carried out sensitively, say, by a UV laser multiphoton excitation-ionization technique. The sensitivity of this detection, i.e. how small a population in Eq. (42) is detectable, determines in essence the magnitude of $\Delta_{\mathrm{pv}}E$ which can be detected without the signal disappearing in the noise. We note that in a real experiment neither the parity selection will be perfect nor will be the time evolution be completely free from external influences (collisions, fields, thermal radiation, etc.), these effects determining the 'noise' background limiting the measurement. On the other hand, the frequency resolution need only be sufficient to detect separate rovibrational levels, and for this a resolution of 1 MHz (often only 10 or 100 MHz, depending on the spectrum) will be sufficient and is readily available by current high resolution laser spectroscopic techniques for instance with the frequency comb based optical parametric oscillators (OPO's) used by us in [104], but also with other laser techniques.

We have tested the method and its sensitivity with the setup shown in Fig. 19 and with an achiral molecule NH_3, where the spectrum is extremely well known and assigned [104]. These experiments, which also demonstrated new hyperfine structure resolution on excited vibrational states of NH_3, show, of course, effective parity conservation in the time evolution, because NH_3 is achiral with levels of well defined parity, which would also be the case for the chiral isotopomer NHDT having a large tunneling splitting in the ground state [96]. However, the test experiment can be used for an estimate of the sensitivity of the current setup and therefore of the values $\Delta_{\mathrm{pv}}E$, which would be detectable. It was concluded that values of $\Delta_{\mathrm{pv}}E \simeq 100\,\mathrm{aeV}$ should be measurable with the current experimental setup, and systematic improvements would allow the measurement of even smaller values of $\Delta_{\mathrm{pv}}E$. Such values are predicted for chiral molecules involving only atoms not heavier than chlorine. Indeed, for the molecule ClOOCl parity violation is calculated to completely dominate over tunneling, making the molecule suitable, in principle, for a measurement of $\Delta_{\mathrm{pv}}E$. In Ref. [103] we have reported a complete simulation of the experiment with preparation and detection steps. The current progress in the experiment depends on obtaining adequate assignments of spectra for suitable chiral molecules identifying positive and negative parity levels as indicated schematically in Fig. 20. This turns out to be a non-trivial task with progress to be discussed in Sec. 4.3. We shall, however, first discuss an interesting conceptual aspect. The prepared parity isomers in the experiment have the character of being at the same time R and S enantiomers corresponding to the wave functions χ_+ and χ_- indicated in Fig. 7, which carry equal weight for λ and ϱ which would be the chiral enantiomers. Such states are classically impossible and sometimes are called 'Schrödinger's cat' after the famous discussion of Schrödinger, which identified quantum mechanical states of a cat which is prepared in a thought experiment in a state where it is at the same time dead and alive (with some probability [203]), a situation which is classically absurd (see also a cartoon in [45]). We have noted occasionally that Schrödinger's 'quantum cat' analogy corresponds to a cruel experiment on an animal, which frequently comes out dead in the final step. We therefore have proposed (for the analogous 'parity isomer') as a better analogy a quantum chameleon which stays alive and only changes color in the course of time, which would be a natural thing for a chameleon to do any way (the change of a spectrum as in Fig. 20 is, of course, the analogue of a change of color [47, 106, 204]).

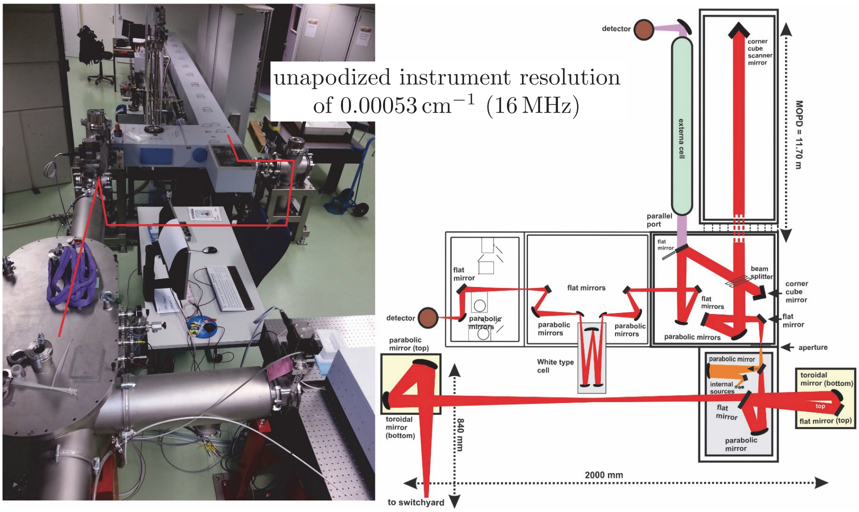
4.3. *Development of spectroscopic techniques and high resolution analyses for chiral molecules and the spectroscopic realization of a quantum chameleon*

Identifying suitable molecules and their high resolution spectra as suitable for 'ultra high' resolution in view of a spectroscopic detection of parity violation in chiral molecules is important for all experimental concepts. Particularly for our approach as proposed in 1986 [100], it is essential to have adequately resolved and analysed spectra in order to identify lines connecting to states of well defined parity in the excited state as discussed in Sec. 4.2.

However, until 1986 there existed not a single example of a chiral molecule, where an analysis of an optical spectrum (IR, VIS, UV) had been achieved with full rovibrational resolution as needed for this approach. Such analyses seemed very difficult although not impossible at this time for molecules of the necessary minimum complexity related to chirality. In the meantime there has been much progress in developments of spectroscopic techniques which is reviewed elsewhere [76, 85, 205–208] (see also many further articles contained in [205]).

Our progress in developing advanced techniques of high resolution laser and also Fourier transform infrared (FTIR) spectroscopy has enabled the analysis of high resolution optical spectra for chiral and achiral molecules with full rotational and vibrational (and sometimes hyperfine-structure) assignments. This occurred over several generations of new developments in techniques. As an example we show in Fig. 21 the currently worldwide highest resolution FTIR spectrometer setup at the

Our group's unique high resolution FTIR setup currently still with the worlds highest resolution (synchrotron-based at the *Swiss Light Source - SLS*)



unapodized instrument resolution of $0.00053\,\mathrm{cm}^{-1}$ (16 MHz)

Fig. 21. Photograph and schematic diagram of the high resolution FTIR prototype (Bruker) spectrometer built at the Swiss Light Source (SLS), using synchrotron radiation in the infrared (after Ref. 209, see also Refs. 206, 208, 210).

Swiss Light Source (synchrotron) built as prototype for our group. Other important developments in our group relate to high resolution diode laser supersonic jet and frequency-comb based spectroscopy with optical parametric oscillators (OPO).

Specifically, progress has been made also on the analysis of high resolution spectra of chiral molecules and Tab. 2 provides a survey of chiral molecules for which parity violation has been studied theoretically and preliminary high resolution analyses of optical spectra are available by now. The table retains only molecules, for which tunneling splittings in the ground state are negligible such that $\Delta_{\mathrm{pv}}E_0$ is an actually measurable ground state energy difference of the stable enantiomers according to the scheme on the right hand side of Fig. 7. These molecules are thus in principle suitable for studies of parity violation by one of the techniques discussed in Sec. 4.2, although not all are really very favourable for such studies, if $|\Delta_{\mathrm{pv}}E|$ is small. Here, we shall discuss one relatively favourable case: 1,2-Dithiine ($C_4H_4S_2$) shown in Fig. 22 [211, 212].

For this molecule theory predicts $\Delta_{\mathrm{pv}}E/(hc) \simeq 1.1 \cdot 10^{-11}\,\mathrm{cm}^{-1}$ (corresponding to $\Delta_{\mathrm{pv}}E \simeq 1\,\mathrm{feV}$) which is well in the range accessible to our current experimental technique. Also the tunneling splitting in the ground state has been estimated to be well below $10^{-20}\,\mathrm{cm}^{-1}$, which guarantees that $\Delta_{\mathrm{pv}}E_0$ is, in principle, measurable [211]. At the same time the barrier for stereomutation is calculated to be around $2500\,\mathrm{cm}^{-1}$, which makes large tunneling splittings at this and higher levels possible,

Table 2. Summary of chiral molecules for which theoretical studies of $\Delta_{\mathrm{pv}}E$ and high resolution spectroscopic analyses exist.

Molecule	$\lvert\Delta_{\mathrm{pv}}E\rvert/(hc\,10^{-14}\,\mathrm{cm}^{-1})$	references
ClOOCl	57.5	103, 152, 186
ClSSCl	130.0	97, 99
$\mathrm{PF^{35}Cl^{37}Cl}$	2.8	181, 208
HSSSH	160	213, 214
$\mathrm{CHF^{35}Cl^{37}Cl}$	^{a})	206, 207, 215–217
CHFClBr	190	54, 55, 194, 195
CDFClBr	190	55, 218
CHFClI	^{b})	219, 220
CHFBrI	^{b})	219, 221
CHDTOH	37	222
CHF=C=CHF	14	152, 223, 224
CHF=C=CHCl	70	152, 224
CHCl=C=CHCl	110	152, 224
D-oxirane ($\mathrm{CH_2CHDO}$)	(0.02)^{c})	225
$\mathrm{D_2}$ oxirane (trans CHDCHDO)	^{c})	226
F-oxirane ($\mathrm{CH_2CHFO}$)	17	196, 227, 228
cyclo-$\mathrm{CH_2CD_2SO}$	^{d})	197, 229
cyclo-$\mathrm{CH_2CHDSO}$	^{d})	197, 229
cyano-oxirane $\mathrm{CH_2CHCNO}$	10	230, 231
cyano-aziridine $\mathrm{CH_2CHCNNH}$	10	230, 232
1,2-Dithiine $\mathrm{C_4H_4S_2}$	1100	211, 212
Alanine ($\mathrm{CH_3CHNH_2COOH}$)	5^{e})	101, 149, 233

Note: a) a preliminary value is small, b) here theory calculated frequency shift values for the C-F stretching fundamental transition, c) small preliminary value, d) preliminary estimate is small, e) strongly conformer dependent and in any case small.

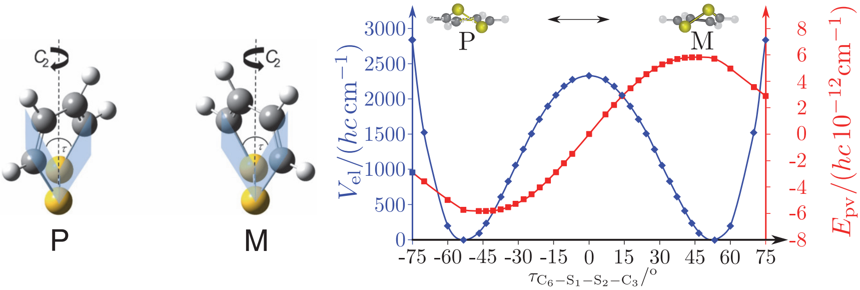


Fig. 22. The enantiomers of 1,2-Dithiine are shown on the left together with the symmetric parity conserving (blue line, left ordinate scale) and antisymmetric parity violating potentials (red line, right ordinate scale) on the right (after [211, 212]).

in a range accessible to our comb-based high resolution laser (OPO) supersonic jet techniques [104, 202] (in addition to high resolution FTIR spectroscopy [206, 212]). It is clear, however, that the analysis of rotation-vibration-tunneling spectra in a molecule of this complexity still presents a major challenge, particularly so at high energy in a very dense spectrum. Clearly progress on similar molecules, also newly designed ones, remains desirable in the future.

At present we shall mention here an example of an achiral molecule of almost comparable complexity, where we have successfully achieved such an analysis of rotation-vibration-tunneling states in a tunneling switching situation [234–236]. This has allowed us to demonstrate non-classical 'quantum chameleon states' involving ground state levels which are separated by energies of corresponding to about $hc \cdot 0.8\,\mathrm{cm}^{-1}$. The example is m-D-phenol which exists in the two planar isomeric forms as syn- and anti- isomer. While the electronic Born-Oppenheimer potential hypersurface has minima of identical energy for these isomers, small zero point energy effects lead to a small ground state energy difference of $\Delta E(\mathrm{syn} - \mathrm{anti})$, which was predicted by theory to be much larger than the ground state tunneling splitting in the symmetric tunneling potential for ordinary phenol, which is about $hc \cdot 0.001\,\mathrm{cm}^{-1}$ [234].

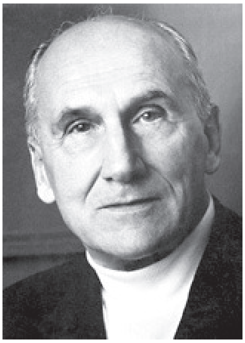
Thus in the lowest vibrational states of m-D-phenol, one has energy eigenstates separated by about $0.8\,\mathrm{cm}^{-1}$ with wave functions corresponding to localized syn- and anti- isomers. The situation is analogous to the asymmetric tunneling situation with parity violation in the right hand side of Fig. 7 with localized wave functions as well. However, the asymmetry in m-D-phenol has a different physical origin and is much larger ($0.8\,\mathrm{cm}^{-1}$ corresponding to about 0.1 meV instead of 100 aeV for parity violation, 12 orders of magnitude smaller). Nevertheless also for the m-D-phenol we have a tunneling switching situation given the modest barrier for isomerization of only about $1000\,\mathrm{cm}^{-1}$. Thus for the torsional level $\mathrm{v_T} = 2$ at $600\,\mathrm{cm}^{-1}$ and higher the eigenfunctions are delocalized and show an approximate symmetry similar to the symmetric case of ordinary phenol, a typical tunneling switching situation. Therefore this molecule has been analysed successfully to demonstrate the 'quantum chameleon states' which might be used for molecular quantum switches [234–236] going far beyond possibilities of 'classical' molecular switches [15–17]. For a detailed discussion of these achiral quantum switches we refer to Ref. 47 (and references cited therein). We conclude here with a brief note on parity violation in isotopically chiral molecules such as PF ^{35}Cl ^{37}Cl and CHF ^{35}Cl ^{37}Cl or D-oxirane (CH_2CHDO) and related ones. As pointed out in Refs. 23, 38, 42, 181, 207, in such molecules the parity violating weak interaction introduces a fundamentally new isotope effect, which arises from the difference in the weak nuclear charge Q_A (Eq. 33) of the different isotopes and not from the mass difference or the difference in nuclear spin as for the ordinary, well- known isotope effects. Because of the nature of the nuclear structure of the isotopes and their values for Q_A, the parity violating energy differences for isotopically chiral molecules are particularly interesting for theory, but they are also typically smaller than in molecules, which are chiral by 'ordinary chemical substitution' of symmetric molecules, say CHFClBr derived from methane or PFClBr derived from PCl_3, see also table 2, and thus they are more difficult for experiments in this respect. This does not exclude, however, larger effects of parity violation in specially selected isotopically chiral molecules. For instance for $CH_3Re^{16}O\ ^{17}O\ ^{18}O$ suggested by us as an interesting candidate at an early time [38], our preliminary calculations indicate much larger values (even by order of magnitude [279]) for the parity violating energy difference than, say, in PF ^{35}Cl ^{37}Cl. We also draw attention here to the possibility of measuring parity violation in achiral spherical top molecules by a level crossing experiment proposed by us in 1995, as reviewed in [23, 47]. While the effects are minute in CH_4 they can be much larger in CF_4, for which recent high resolution spectroscopy might be a first step towards such experiments (see [277, 278] and references cited therein).

5. Parity violation and biomolecular homochirality

In his Nobel prize lecture 1975 on ‘Chirality in chemistry’ [10], V. Prelog concludes with a brief statement on the question of biomolecular homochirality as shown in Fig. 23. Prelog refers here to the observation that in the biopolymers of life (with chiral amino acids in the proteins and chiral sugars in DNA) only the L-amino acids are used and only the D-sugars. Strictly speaking in other circumstances (not in the biopolymers) the other enantiomeric forms do occur also naturally in biological processes. Also the uniqueness of selection, say, of the whole series of natural L-amino acids depends upon the convention used. For instance with the R, S nomenclature there are not only S-amino acids selected. For example L-cystein is selected as D/L nomenclature identifies it as ‘L’ enantiomer by convention, but when using the CIP convention it will be R-cystein as this corresponds to L-cystein according to the rule in this case. But the basic fact remains true, as stated by Prelog, that for each particular amino acid and each sugar only one enantiomer occurs in the biopolymers.

Why this is so has been an enigma for more than a century, the phenomenon has been noted (with limited knowledge) already by Pasteur [4–7] and by Fischer

Chirality and Biomolecular Homochirality



’The time at my disposition also does not permit me to deal with the manifold biochemical and biological aspects of molecular chirality. Two of these must be mentioned, however, briefly. The first is the fact that although most compounds involved in fundamental life processes, such as sugars and amino acids, are chiral and **although the energy of both enantiomers and the probability of their formation in an achiral environment are equal, only one enantiomer occurs in Nature**; the enantiomers involved in life processes are the same in men, animals, plants and microorganisms, independent on their place and time on Earth. Many hyptheses have been conceived about this subject, which can be regarded as one of the first problems of **molecular theology**. One possible explanation is that the creation of living matter was an extremely improbable event. which occured only once.’

- Vladimir Prelog (ML), Nobel Lecture, 12 Dec 1975

Fig. 23. Citation on chirality and biomolecular homochirality from Ref. 10 (emphasis added here).

[237] for instance, identifying this 'homochirality' as a simple chemical signature of life. While the statement of this long standing enigma by Prelog is thus essentially correct, we have noted in many friendly private discussions with him in Zurich in the early 1980ies and in the publication dedicated to him at his 80th birthday meeting [100], that the premisses are incorrect: Because of parity violation the energies of the enantiomers in an achiral environment are in fact not equal (that one might consider free space as chiral is a separate story, see [44, 48] for some of the history).

The question is then, how important this small asymmetry arising from parity violation will be for the origin of biomolecular homochirality [39]. We anticipate here the short answer: We do not know, but at least one can say that the discovery in 1995 [149] of an increase by a factor of 10 to 100 of parity violating energy differences $\Delta_{\mathrm{pv}}E$ calculated from theory has made the possibility of an important effect of parity violation in the evolution of biomolecular homochirality more likely than it seemed before, but in any case the question remains open. There is an obvious relation to the other open question concerning the origin of life. How did life arise from 'non-living matter'? This question, which refers to the frontier between the non-living and living refers to what is the very nature of life. The question 'What is life?' also has a long history with many debates in the scientific and the non-scientific literature. Schrödinger asked the question from a physicist's perspective in his famous little book arising from lectures in 1943 [238]. We shall take here the pragmatic point of view that we can distinguish the 'living' from the 'non-living' by inspection in a fairly straight-forward way [45]. On these three open questions there exists, indeed, a huge literature, which we cannot refer to in any meaningful way here. In [39, 45, 48] we have provided more extended discussion related to various questions on life in a 'decision diagram' or flow diagram reproduced here in Fig. 24. Without going into details we summarize here that at every step the related question is really open. However, there are for each step 'opinions' from what we have called communities of belief [38, 41, 45, 48]. For instance, whether life is rare in the universe, possibly singular, only existing on our planet, as surmised by Monod [239] and perhaps Prelog [10], or else whether it is frequent, as seems to be the current majority opinion, according to some informal, non-representative 'polls' in lectures [45, 48], is in reality completely open [41, 43, 48]. This corresponds to the first step on top in the diagram of Fig. 24 (see also the reviews [45, 48]).

Here we shall focus on the question on homochirality addressed in the lower part of the diagram. One has essentially two large communities of belief (with numerous different 'denominations' within each community). The first one assumes that homochirality arises simply by a *chance selection* in the early stages of the evolution, either pre-biological (non-living matter) or a little later in early living species. This we have called the '*de facto*' selection (by chance). The other community assumes that the '*de lege*' asymmetry arising from parity violation has been important and the selection occurred *by necessity*, preferring one form over the other in analogy to the diagram in Fig. 7. The question could, in principle be answered by observation of possibly many different forms of life on exoplanets [240–242], which might be

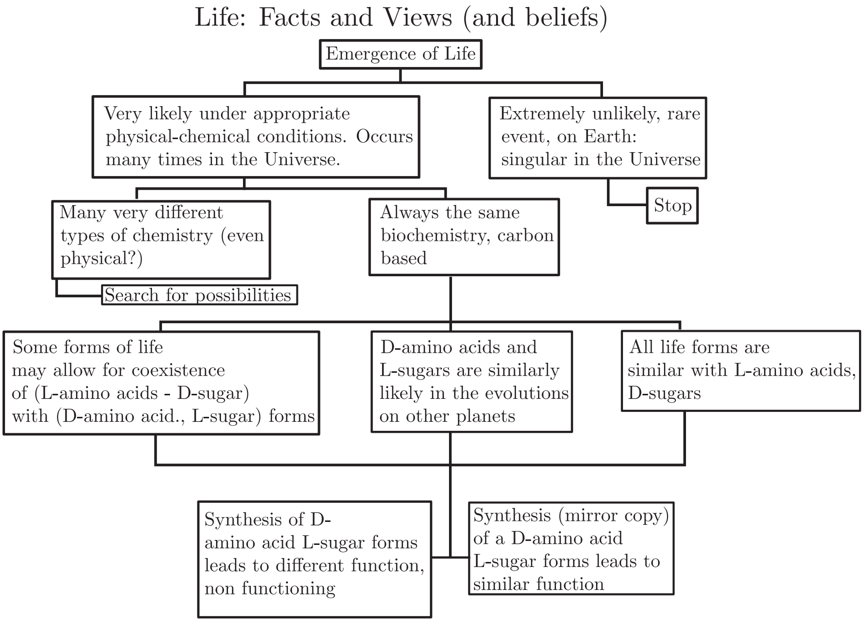


Fig. 24. Summary as ‘flow diagram’ for opinions and beliefs on the emergence of life and homochirality (modified after Refs. 45, 48).

possible by a spectroscopic search for a systematic homochirality on these planets [42, 45] or perhaps within our solar system by space flight. The *de facto* hypotheses would predict a statistical distribution of ‘L’ or ‘D’ homochirality (if any). The *de lege* hypotheses would predict a preponderance of one form (perhaps even a unique selection of always the same form). Numerous mechanisms have been proposed to explain the origin of biomolecular homochirality. Our lack of understanding does not arise from an absence of such explanations. Indeed there are many different more or less plausible explanations, but we do not know which one is correct.

The long list of existing proposals, can clearly be grouped into broad classes of ‘*de facto*’ selection (by chance) and ‘*de lege*’ selection (by necessity). We shall not enter into any further detailed discussion here, but we note that some of these have had firm believers with heated debates among the different communities of belief and sometimes false statements of evidence (see the discussions in [39, 41, 45] for further information). The question arises on how to obtain conclusive evidence. One approach might be to repeat total synthesis of life and evolution in the laboratory, clearly a difficult enterprise so far without much success (see e.g. [243, 244]). We note here, that so far not even the total synthesis of an enantiomeric copy of a simple existing bacterium has been successful, although already proposed in 1990 [245].

Another approach would be to investigate the conditions for certain mechanisms by systematic experiments complemented by theory and thereby approach an answer in a stepwise way. In this context we can refer to the lectures by Blackmond and Soai at this meeting [272, 273]. There has been a most interesting series of experiments by Blackmond and coworkers [246–252] in relation to the famous autocatalytic Soai mechanism [253–258] (see also [259]). Using minor perturbations by substituting 'heavy' (non-hydrogen) isotopes such as $^{12}\mathrm{C}/^{13}\mathrm{C}$ or $^{14}\mathrm{N}/^{15}\mathrm{N}$ an estimate was made about the threshold energy differences (e.g. in terms of $\Delta\mathrm{G}^{\neq}$ in transition states) that can induce an amplification to homochirality in a Soai-type mechanism. This threshold was found to be about $10^{-5}\,\mathrm{Jmol}^{-1}$. While such small values are, indeed, interesting, they are obviously much larger than anything that might be expected to arise from parity violation, perhaps $10^{-10}\,\mathrm{Jmol}^{-1}$ or at most a little larger. Sometimes this gap on the order of 4 to 5 orders of magnitude has already been interpreted as proving the unimportance of parity violation in the evolution of biomolecular homochirality. However, such a conclusion is quite unjustified as it refers only to relatively simple mechanisms such as the Soai reaction. It is possible and even likely, that real-life mechanisms in early prebiotic or early biotic chemistry would be much more complex and more sensitive to small energy effects. In that sense the result, that energy differences on the order of $10^{-5}\,\mathrm{Jmol}^{-1}$ are estimated to suffice for a selection of homochirality on short time scales in simple autocatalytic mechanisms would lead to rather optimistic expectations to bridge the remaining gap of a few orders of magnitude with more sensitive and more complex mechanisms on longer time scales.

It has sometimes also been argued that a chemical evolution of homochirality is impossible on long time scales because chiral molecules in reactive environments would always racemize on long time scales. This argument is obviously invalid, as we have 'living proof' in the long lived existing homochirality of life, which, indeed, has used for millions of years chiral molecules in a permanently reactive chemical environment and has successfully avoided racemization by a 'complex autocatalytic mechanism', if one may say so.

Without entering into any further discussion of the many other suggestions and hypotheses, we conclude here with the statement that at present there is simply no proof or even compelling argument to exclude either a *de lege* mechanism (involving electroweak parity violation) or a *de facto* mechanism (by chance). Both are perfectly possible origins of today's biomolecular homochirality and it remains our task to find out, which of the two applies, possibly both under different circumstances.

6. Conclusion and outlook

Chiral molecules are of greatest importance for many aspects of chemistry and they are the building blocks of biological matter. The relation of chirality with space inversion symmetry establishes a close connection with fundamental physics. Parity violation changes our concepts for the stereochemistry, structure and dynamics of chiral molecules. While tunneling according to Hund's treatment dominates over parity violation in transiently chiral molecules such as hydrogen-peroxide (HOOH) [94, 95], the chiral ammonia isotopomer (NHDT) or the aniline isotopomer ($\mathrm{C_6H_5NHD}$), for example [96, 274], we know now that for ordinary chiral molecules, which are stable for days or years, at least, such as CHFClBr, alanine or other amino acids, sugars etc., parity violation dominates completely over tunneling and is the decisive factor for a conceptually correct understanding of their structure and energetics [23, 100].

In contrast to the classical picture of van't Hoff with two symmetrically equivalent enantiomers with exactly equal energies, there is a small but physically significant and in principle measurable energy difference $\Delta_{\mathrm{pv}}E$ between their ground states, resulting in a non-zero reaction enthalpy and free energy for stereomutation. The new and much larger orders of magnitude discovered for this energy difference in our theoretical work from 1995, has in the meantime been confirmed independently by theoretical work in other groups and can in this sense be considered to be well established (see Sec. 3). This has also improved the outlook for spectroscopic experiments, which are ongoing (see Sec. 4), although still without conclusive results, so far.

However, much of the spectroscopic ground work for such experiments has been completed by now and one can expect most significant results for all of the possible outcomes of such experiments:

(1) If experiments confirm the theoretically predicted values for $\Delta_{\mathrm{pv}}E$, then one can analyse the results of the precision experiments in terms of the standard model of particle physics (SMPP) in a range of quantum systems not yet tested in previous experiments, for example in molecules involving only 'light' nuclei up to, say, Chlorine.
(2) If one finds, on the other hand, values of $\Delta_{\mathrm{pv}}E$ different from the theoretical predictions, this will lead to a fundamental revision of current theories for $\Delta_{\mathrm{pv}}E$ with even the potential for 'new physics'. Surprises are possible!
(3) Finally, a profound experimental and theoretical understanding of $\Delta_{\mathrm{pv}}E$ in chiral molecules can be a first step towards a possible understanding of the implications of parity violation for the evolution of biomolecular homochirality.

We have obtained also further results concerning fundamental concepts of physical-chemical stereochemistry. The possible preparation of 'parity isomers' of chiral molecules introduces the structural concept of 'bistructural' molecules (being 'quantum chameleons', at the same time R and S enantiomers but very different from a 'racemic mixture'). The time evolution of the spectra of these bistructural molecules corresponds to the new intramolecular primary process of parity change with time arising from parity violation by the weak nuclear force. The concept of such bistructural isomers can be extended to other types of isomers and has potential for quantum technology in the more distant future. Based on high resolution spectroscopic results, we have already demonstrated such exotic chameleon states for bistructural syn- and anti- m-D-phenol [234–236] and also for different nuclear spin symmetry isomers (ortho- and para-) in ClSSCl [99].

Main Ideas and Observations

We live in a world		Symmetry
1.	of matter (not antimatter)	C (CP, CPT)
2.	of L-amino acids and D-sugars (and not D-amino acids and L-sugars) in ordinary life (proteins, DNA, RNA)	P
3.	where time runs forward (and not backwards) (also combinations CP, CPT,...)	T

What is the origin of these observations? (*de facto* vs. *de lege*?)
Are they basic 'quasi-fossils' of the evolution of matter and life?

Fig. 25. Three fundamental observations in our world, with so far unexplained relation to fundamental symmetries and their violation (after Ref. 45).

We conclude here with a brief discussion going beyond these now well established results. Charles Darwin is occasionally quoted with a statement 'It is as absurd to think about the origin of life as it is absurd to think about the origin of matter'. However, if we do start this 'absurd thinking' we note three basic 'asymmetries' in our world (Fig. 25). We might consider these as 'quasi-fossils' carrying information about the evolution of matter and life [45]. It turns out that the asymmetries C and CP between matter and antimatter, while experimentally and theoretically known in the SMPP [260], do not seem to be able so far to explain quantitatively the current preponderance of matter over antimatter in the universe [275, 276]. There remain open questions on this quasi-fossil from the origin of matter. Similarly, the observation of the current 'homochirality of life' (with L-amino acids in proteins and D-sugars in DNA) has contradictory explanations (*de facto*, by chance, or *de lege* - involving parity violation, see Sec. 5) and we do not know, which of the explanations is correct. The interpretation of this quasi-fossil from the origin of life [45] remains completely open in spite of much work, which exists already.

We can finally go beyond these two asymmetries by considering the general scheme for chiral molecules and their antimatter counter parts, in Fig. 26, which can be considered 'antimatter stereochemistry' (where we use the 'physical nomenclature' L and R for the stereoisomers and L^* and R^* for their antimatter counterparts) [62]. As we have discussed, CPT symmetry, which so far has never been found violated and is considered to be exact in the current SMPP, requires the pair of molecules L and R^* to be exactly equivalent energetically (and similarly for R and L^*). We have discussed that this can be used for a most sensitive spectroscopic test

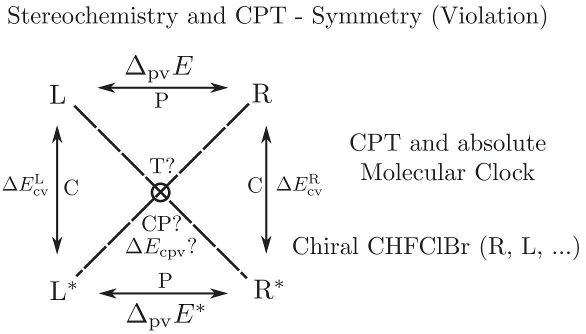


Fig. 26. Stereochemistry with antimatter (using the 'physical' notation L and R for enantiomers of ordinary matter, and L* and R* for antimatter) as a possible test for CPT symmetry violation (after Refs. [23, 62, 107]).

for CPT symmetry [23, 107], much more sensitive than other tests that have been made or proposed so far [261–266] (see also Ref. 47). CPT symmetry can be related to a 'non-observable' which can be considered to concern the observation of a generalized direction of time when including antimatter with an absolute chiral molecular clock for example [41–43]. Whether a violation of CPT symmetry will ever be found remains open, but even at the level of a direction of time in ordinary matter there remains an open question whether the second law of thermodynamics concerning the increase of entropy with time is due to a *de lege* or a *de facto* symmetry violation [23, 41–43], and there are further interesting alternatives to be mentioned [267]. We might refer in this context to various results and searches on the violation of time reversal symmetry and also its relation to the observation of the permanent electric dipole moment of the electron [261, 268–270] expected to be extremely small in the current SMPP (see also the review in Ref. [23]). Thus there remain numerous open questions related to 'chiral matter' in general and chiral molecules, where we do not know the answers yet. But we can conclude by quoting with David Hilbert: 'Wir müssen wissen! Wir werden wissen!' (We must know. We shall know.)

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