CHIROPTICAL SPECTROSCOPIES FOR INVESTIGATING SOFT MATTER AND ORGANIC-BASED CONDUCTING MATERIALS

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THREE PARTS:

1) **Chiral systems** and **chiroptical spectroscopies**:

   - Optical Rotation (OR) ↔ Circular Dichroism (CD)
   - electronic transitions
   - vibrational transitions

   other less common techniques:
   - Raman Optical Activity (ROA)
   - Circularly Polarized Luminescence (CPL)

2) **Applications**: **Biological and pharmaceutical molecules**
   - Most frequent: *Configurational assignment*
   - *Conformational Studies of Proteins, Peptides, DNA bases (in solution)*

   **Supramolecular structures**: (bio)molecules-surfactants, fibrils, gels
   - 2a) “soft matter”: peptide-based gels
   - 2b) Interaction of a Reverse Micelle and a Natural Product (dimethyl tartrate)

3) **Applications**: **Molecules for material science**
   - 3a) Helicenes
   - 3b) Electroactive thiophene-based systems
   - 3c) Carbon nanotubes
Chirality

1848 Pasteur Chiral system: not superimposable to its mirror image.

Asymmetric Carbon: S and R enantiomers

Axial chirality: Helix

• CHIROPTICAL TECHNIQUES ARE APPLICABLE TO INTRINSICALLY DISSYMMETRIC MOLECULES, i.e. WITH NO INVERSION CENTRE OR MIRROR SYMMETRY.

• CHIRAL SYSTEMS COME IN PAIRS (ENANTIOMERS)...with OPPOSITE CHIROPTICAL SPECTRA (when one is more abundant: Homochirality)
Importance of chirality

life science: aminoacids, DNA bases, carbohydrates
… are homo-chiral
interactions with biomolecules influenced by chirality:
ex. biochemical activity of drugs: different enantiomers have different
…..effects, fragrances and natural extracts …..

material science: biosensors, systems for chiral recognition
non-linear interactions with electromagnetic fields

**Chiral recognition:** handshake
right-to-right  left-to-left  left-to-right  right-to-left
Chiral recognition **between compounds**

Chiral interaction **molecule-light**: ‘chiral’ light

In order to detect molecular chirality, some sort of chiral probe must be used: Right- and left-circularly polarized light beams are mirror-image chiral systems and so can act as chiral probes:

Chiral molecules respond slightly differently to right- and left-circularly polarized light: a difference in absorption corresponds to **Circular Dichroism** and a difference in refractive index leads to **Optical Rotation**.
How to generate a circularly polarized wave:
superposition of two waves polarized in two perpendicular planes, with same amplitude and wavelength and
with a phase difference of 90 degrees between them.

Fig. 3 Diagrams illustrating a) the effect of a PEM on a linearly polarized light beam and b) the result of + or - 90° retardation
Linearly polarized light:

Linearly polarized light can be seen as the sum of two circularly polarized components of same magnitude and opposite phase.
Optically active system: how does it change transmitted light?

**Incident linear polarized wave**

**ORD:** optical rotatory dispersion

**Wavelength Dependence of Optical Rotation**

![Diagram of incident and emergent light](image)

**Circular Birefringence**

Refractive indexes for left and right circularly polarized light are different.

*we measure rotation angle: \( \alpha \) (degrees)*

**CD:**

**Circular dichroism**

**Ellipticity**

Left and right components are differently absorbed.

*we measure ellipticity angle: \( \Theta \)*

*or absorbance difference: \( \Delta A \)*

For small angles: \( \Delta A \approx \Theta/32.98 \)
Incident plane polarized light: polarization of the light out of an optically active medium.

Both effects are observed in general:

**Circular Birefringence:**
The two circular components have different velocity, \( n_L \neq n_R \)

Major axis is no more parallel to the initial polarization direction

\[ \rightarrow \text{Rotation of the polarization plane} \]

**Circular Dichroism**
The two circular components are absorbed differently, \( A_L \neq A_R \)

\[ \rightarrow \text{Elliptic polarization} \]

\[\begin{align*}
[α]_λ &= \alpha \cdot 100 / (d \cdot c) \\
[θ]_λ &= 32980 (A_L - A_R) / (d \cdot c)
\end{align*}\]

\[\hat{n} = n + ik\]

\[\begin{align*}
\alpha &= (n_L - n_R) 180 \, d / λ \\
θ &= (k_L - k_R) \, 180 \, d / λ
\end{align*}\]
Normal optical rotation (OR):
For an optically active compound, in a spectroscopic region with no absorption bands, the Optical Rotation Dispersion (ORD) curves are monotonic continuous functions (positive or negative).

Circular Dichroism: In correspondence of an absorption band there is a slightly different absorption between left and right circularly polarized light.

In correspondence with a Circular Dichroism band,
Optical Rotation Dispersion becomes anomalous.

\[ \Delta \varepsilon = \varepsilon_L - \varepsilon_R \]
Circular Polarization Spectroscopy of Chiral Molecules

At molecular level:

**optical activity** ⇔ **asymmetry of electronic distribution**

The absorbed light induces an elicoidal shift of charges, this explain the preferred absorption of one circularly polarized component.

Fig. 1 Diagrams illustrating the spatial patterns of electric field motion for left and right circularly polarized radiation.

(+) dimethyl-L-tartrate

(-) dimethyl-D-tartrate
Absorption band
Electric dipole transition moment

\[ D = \mu \cdot \bar{\mu} \neq 0 \]

\[ D = 92 \cdot 10^{-40} \cdot \varepsilon_{\text{max}} \cdot \frac{\Delta \lambda}{\lambda_{\text{nm}}} \]

\( \lambda = 265 \text{ nm} \quad \varepsilon = 6400 \)
\( \lambda = 234 \text{ nm} \quad \varepsilon = 15000 \)
\( \lambda = 380 \text{ nm} \quad \varepsilon = 7600 \)

Optically active transitions

A 0→m transition to be optically active needs both a transition electric dipole moment \( \mu \) and a transition magnetic dipole moment \( m \).

\[ R_{0m} = \mu_{0m} \cdot m_{0m} \]

\[ R \approx 23 \times 10^{-40} \Delta \varepsilon_{\text{max}} \frac{\Delta \lambda}{\lambda_{\text{max}}} \]

By analogy with the dipole strength associated with normal absorption, we can define a rotational strength that indicates the intensity, or probability, of a CD transition.

Optical activity requires both a finite \( \mu \) and a finite \( m \). The product of these two vectors corresponds to a helical displacement of charge.
Selection Rule for CD
-Charge displacements ($\mu$) that accompany absorption events are linear. **electric dipole allowed transitions**
- The circular component (if present) generates a magnetic dipole ($m$). Transitions that generate a magnetic dipole are **magnetically allowed**.
- Optical activity requires both a finite $\mu$ and a finite $m$. The dot product of these two vectors is a pseud-scala and is associated to a helical displacement of charge.

$$R_{0m} = \mu \cdot m \neq 0$$ if and only if both $\mu$ and $m \neq 0$ and **non ortogonal**

For molecules with inversion symmetry $i$ there are states $\Psi_g$ e $\Psi_u$:

$$\vec{\mu}_{0m} \neq 0$$ per $g \longleftrightarrow u$

$$\vec{m}_{0m} \neq 0$$ per $g \leftrightarrow g \ o \ u \longleftrightarrow u$

$$R_{0m} = 0$$

For molecules with a symmetry plane $\sigma$ there are states $\Psi^+$ e $\Psi^-$:

$$\vec{\mu}_{0m} \neq 0$$ per $+ \longleftrightarrow -$ $$R_{0m} = 0$$

$$\vec{m}_{om} \neq 0$$ per $+ \longleftrightarrow +$, $-$ $-$
CHIROOPTICAL TECHNIQUES COMPRIS E
-OPTICAL ROTATION (OR and ORD),
-CIRCULAR DICHROISM (CD)
  (IN THE IR-NIR: VCD AND IN THE UV-Vis-NIR: ECD)
-CIRCULARLY POLARIZED LUMINISCENCE (CPL)
-RAMAN OPTICAL ACTIVITY (ROA)

CIRCULAR DICHROISM
ECD: UV-VIS range 800-180 nm electronic transitions

VCD: IR range 800-4000 cm⁻¹ vibrational transitions:
  "fingerprint" region

NIR-VCD: NIR range 850-1750 nm
  -vibrational overtone transitions VCD
  -electronic transitions
  (metal-ions and highly conjugated materials). ECD

ORD: optical rotation dispersion (far from absorbtion bands)
Circularly Polarized Luminescence
CPL

Raman optical activity
ROA

\[
(\Delta I^\alpha)^\alpha_{g_1,g_0} = (I^\alpha_R)^\alpha_{g_1,g_0} - (I^\alpha_L)^\alpha_{g_1,g_0}
\]

SCP-ROA
Circularly Polarized Luminescence CPL

CPL apparatus:
PEM ¼ photoelastic modulator;
PM photomultiplier tube).
LED sources, LASER, optical fiber indicated by arrows, in
the vicinity of the sample position.
Raman optical activity (ROA)

ROA measures a tiny difference in the intensity of Raman scattering from chiral molecules in right (R)- and left (L)-circularly polarized incident light:

$$I_R^R + I_L^L$$

$$I_R^R - I_L^L \neq 0$$

ROA has the same relationship to Raman as ECD does to UV absorbance, and as VCD to IR.
2) applications: *biological and pharmacological molecules*

* Configurational assignment

**DETERMINATION OF THE ABSOLUTE CONFIGURATION**
DUAL AROMATASE-SULFATASE INHIBITORS
by Vibrational Circular Dichroism (VCD) and
Electronic Circular Dichroism (ECD) Spectroscopy

Experimental spectrum, calculation of expected spectra for a given configuration after careful conformational analysis.
Info gained: configuration assignment, conformational information

\[
\begin{array}{|c|c|c|c|c|c|c|c|c|}
\hline
& \tau_1 & \tau_2 & \tau_3 & \Delta G_{\text{cal/mol}} \ (6-31G^*) & \text{pop-}\Delta G \ (6-31G^*) & [\alpha]_D & \Delta G_{\text{cal/mol}} \ (TZVP) & \text{pop-}\Delta G \ (TZVP) \\
\hline
1 \ pseudo-\Lambda & -138.0 & -165.7 & 9.9 & 0.0 & 22.9\% & 343.7 & 0.0 & 21.1\% \\
2 \ pseudo-\Lambda & -140.6 & 14.0 & 9.8 & 71.5 & 20.3\% & 529.2 & 420.4 & 10.2\% \\
3 \ pseudo-\Lambda & -136.7 & -147.9 & -144.1 & 115.5 & 18.8\% & 154.1 & 47.1 & 19.4\% \\
4 \ pseudo-\Lambda & -135.4 & 30.2 & -144.0 & 305.0 & 13.6\% & 250.1 & 189.5 & 15.2\% \\
\hline
1 \ pseudo-\Delta & 142.9 & 140.4 & 148.0 & 690.9 & 7.0\% & -390.9 & 718.5 & 6.1\% \\
2 \ pseudo-\Delta & 163.3 & -36.0 & -11.5 & 705.3 & 6.8\% & -322.9 & 171.9 & 15.7\% \\
3 \ pseudo-\Delta & 160.3 & 146.2 & -10.1 & 712.2 & 6.7\% & -649.0 & 690.9 & 6.4\% \\
4 \ pseudo-\Delta & 143.5 & -39.3 & 147.3 & 1041.7 & 3.8\% & -84.3 & 746.1 & 5.8\% \\
\hline
\end{array}
\]

VCD and Absorption spectra:
*R* configuration calculated compared with (+) enantiomer measured
VCD and Absorption spectra:

$R$ configuration calculated compared with (+) enantiomer measured
ECD spectra: $R$ configuration established by comparing calculated spectrum with that measured for (+) enantiomer
2) applications: *biological and pharmaceutical molecules*

*Conformational Studies of Proteins, Peptides, DNA bases (in solution)*

Study of the secondary structure of proteins in solution

CD spectrum (a) and absorption spectrum (b) of poly-L-alanine in α-helical structure. Bands are assigned to n → π* transition at 220 nm and to the parallel and perpendicularly polarized π → π* transitions at 204 and 190 nm. (After Quadrifoglio, F., Urry, D. W. (1968), J. Ann. Chem. Soc. 90, 2755)
An example: determine the melting point of a protein in different environments
2a) “soft matter”: peptide-based gels

CIRCULAR DICHROISM SPECTRA OF GEL FORMING PEPTIDES
A pair of oppositely charged peptides, self-repulsive but mutually attractive, that co-assemble into hydrogels: the effect of chirality on the rate of gelation as well as on the mechanical properties of the biomaterial have been investigated

Positive sequence:
+ + + + + +

Negative sequence:
- - - - - -

homochiral vs. heterochiral specificity.

(Homochiral: L-KWK+ L-EWE and D-KWK+ D-EWE)

(Heterochiral: L-KWK+ D-EWE and D-KWK+ L-EWE)

Left to right: heterochiral pair, homochiral pair

<table>
<thead>
<tr>
<th>Appearance</th>
<th>Kinetics of gelation</th>
<th>Mechanical strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>More transparent</td>
<td>slowness</td>
<td>stronger</td>
</tr>
<tr>
<td>Opaque, white</td>
<td>faster</td>
<td>weaker</td>
</tr>
</tbody>
</table>

L-L or D-D
L-D or D-L
The effect of chirality on the rate of gelation as well as on the mechanical properties of the biomaterial have been investigated.

Dynamic rheological characterization of heterochiral and homochiral peptide pairs. (A) Homochiral pairs lead to higher $G'$ values after 48 h of gelation; (B) heterochiral pairs gelate faster and lead to higher $G'$ values within the first 4.5 h. Homochirality confers mechanical advantage while heterochirality confers kinetic advantage.

SAXS monitoring of the gelation process: time evolution of the 2D average cross-section of the peptide fibers.
Effect of supramolecular organization onto the peptide secondary structure.

Different behavior homochiral vs. heterochiral: Circular Dichroism

Secondary structure estimation:
Solution: 75% random coil  25% beta
Homochiral gels: 25% random coil  75% beta
Gelation process monitored by Circular Dichroism
Time evolution of CD spectra of homochiral mixtures

Time evolution of CD spectra of homochiral mixture LL in cyclodextrin
2b) Interaction of a Reverse Micelle and a Natural Product (dimethyl tartrate)

The interaction of D-dimethyl-tartrate (DDT) and soy-Lecithin (LCT) in an apolar solvent $\text{C}_6\text{D}_{12}$ or Bis(2-ethylhexyl)sulfosuccinate Sodium salt (AOT) in $\text{CCl}_4$

LCT and AOT in apolar solvents form reverse micelles
IR Spectra in the Fundamental ($\Delta v=1$) OH-stretching region

- **a**: DDT/CCl$_4$
- **b**: DDTsolid
- **c**: DDT/LCT/C$_6$D$_{12}$
  - R=1.5
- **d**: DDT/AOT/CCl$_4$
  - R=1.5
VCD spectra of DDT and DDT-LCT and DDT-AOT in the mid-IR deformation and CC-stretching region

![Graphs showing VCD spectra for different samples: DDT/CCl₄, DDT/DMSO, DDT/AOT/CCl₄, DDT/LCT/C₆D₁₂.](image)
VCD spectra of DDT and DDT-LCT and DDT-AOT in the mid-IR C=O-stretching region

SIMULATION OF ONE DDT MOLECULE AND ONE DMSO MOLECULE

- calc. vacuo
- av. a, b, c, d, e, f
- Exp-CCl4
- Exp. DMSO
HELICENES

ARE SYSTEMS OF n ORTHO-FUSED BENZENE RINGS (n=5,6,7, etc.)

POSSIBLY DECORATED OR WITH SIMPLE SUBSTITUTIONS

At Room Temperature: Simple Helicenes with \textbf{n}=5 racemize
Simple Helicenes with \textbf{n} \geq 6 enantiomerically stable

They possess large \(\pi\)-conjugation and
large specific optical rotation (for \(n=6\), \([\alpha]_D \approx 4000\))
ECD spectra of chiral mono-aza-pentahelicenes: racemization rates
n=6 (Hexahelicenes)

ECD, VCD, ROA, CPL

Significative to obtain these spectra:
- important models for all chiroptical technique
  and for the corresponding calculations
- conjugation and chirality
VCD and IR spectra for (-)-2-Br-hexahelicene compared with spectra calculated for M-2-Br-hexahelicene.
Raman Optical Activity (ROA)
Raman and spectra for (-)-2-Br-hexahelicene

BEHAVIOR SIMILAR TO CORONENE (and possibly with other graphite bidimensional molecules)

J. Phys. Chem. B 2013, 117, 2221-2230
VCD Spectra of 5-aza-Hexahelicene

IMPORTANT MODE PROVIDING INTENSE VCD is a localized out-of-plane CH bending close to N.
Comparison of experimental and calculated (M-structure) ECD and Circularly Polarized Luminescence (CPL) spectra for 5-aza-hexahelicene

The ECD spectrum at long wavelength in correspondence of substitution sensitive bands, has been expanded.

### Table:
| λ (nm) | D   | R_{vel} | R_{length} | |μ| | |m| | angle |
|--------|-----|---------|------------|------|------|------|------|-------|
| 337    | 6521| -7.40   | -7.01      | 0.32 | 0.23 | 114  |
| 317    | 3507| 1.18    | 0.89       | 0.23 | 0.30 | 87   |
| 295    | 237389| 738.70  | 766.32     | 1.92 | 4.20 | 66   |
| 374    | 10258| -18.00  | -17.93     | 0.40 | 0.20 | 161  |

rotational strengths (R 10^{-44} esu^2 cm^2) electric and magnetic transition dipoles, |<0|μ|e>|, |<0|m|e>| (a. u.) and angle formed by them (if lower than 90° it corresponds to positive rotational strength). The lowest three transitions calculated at the ground state equilibrium structure are reported in black; the transition at the optimized structure of the excited state is reported in red.
3b) Electroactive thiophene-based systems

poly-3-(S)-2-methylbutylthiophene PMBT

CD spectra for good and bad solvents

Figure 1. a) UV/Vis absorption spectra and b) CD spectra of PMBT in various CHCl₃/CH₃OH mixtures (---100% CHCl₃, - - - 93% CHCl₃; ......86% CHCl₃).
CD spectra for films

Figure 7. Electronic absorption spectra of spin-coated PMBT film during in situ heating from 28 to 260 °C and cooling to room temperature.

Figure 9. Circular dichroism spectra of a spin-coated PMBT film during in situ heating from 80 to 240 °C.
Chirality in organic polyconjugated electroconductive materials important for:
- ordered chain assembling induced by chirality
- for second-order NLO applications
- sensors designed for the detection of chiral analytes.

Attaching chiral pendants to an electroactive polyconjugated backbone, generally results in modest chirality manifestations.

inherently chiral polythiophene
INHERENTLY CHIRAL POLYTHIOPHENES:
CIRCULAR DICHROISM SPECTROELECTROCHEMISTRY

Calc. enantiomerization barrier 167 kJ mole$^{-1}$
CD spectrum: typical exciton coupling
Configuration assignment by comparing experimental and calculated spectrum

Electrochemical polymerization of inherently chiral 2,2’-Bis(2,2’-bithiophene-5-yl)-3,3’-bithianaphthene (T4-BT2).
MALDI experiments show a prevalence of dimers, and a non negligible presence of trimers.
Exciton coupling mechanism

electric dipole allowed transitions: two interacting chromophores give a couplet of CD bands

Two degenerate coupled oscillators

\[ \varepsilon^\pm = \varepsilon \pm V \]
\[ V = \frac{\mu^a \cdot \mu^c - 3\hat{R}_{AC} \cdot \mu^a \mu^c \cdot \hat{R}_{AC}}{R_{AC}^3} \]

If \( \mu \) perpendicolar to \( R_{AC} \)

\[ R^{\pm} = \pm \frac{\varepsilon \mu^2 R_{AC} \sin \tau}{4\hbar} \]
\[ \varepsilon^{\pm} = \varepsilon \pm \frac{\mu^2 \cos \tau}{R_{AC}^3} \]
CD data show that the process is fully reversible and repeatable, some loss of electroactivity is observed after several repeated slow voltammetric scans. Parallel in situ ESR experiments show the progressive formation of a radical state with maximum density signal at 0.52 V (Fc+/Fc) confirming the presence of a polaronic state. Angew. Chem. Int. Ed. 2014, 53, 2623–2627
Not simple exciton coupling model, axial chirality similar for the neutral and charged case.

Negative band at 400 nm is due to a nearly degenerate couplet, neutral and the charged species, the positive feature at 500 nm is due to the HOMO-LUMO transition, it is altered in the charged state where a positive feature at 850 nm is calculated.
DFT and TD-DFT calculations on oligo-(S)-(+)T4-BT2, both in the neutral and charged state, allow to reproduce UV and CD spectra quite satisfactorily: all species give a negative band at 400 nm, the positive band at 500 nm is strongly dependent on the charge state, its intensity decrease goes together with the presence of a band of the same sign at 800 nm.

Calculations shed light on structural and electronic properties of the oligomers: characterize the aromatic/quinoid structure of the neutral/charged systems, evidence the flatness of the tetrathynil ribbons in the charged species and establish the localization of the polaron defect.
As a preliminary test for the enantiorecognition ability, the CV patterns (S)-(−) and (R)-(+) N,N-dimethyl-1-ferrocenylethylamine, used as chiral probes, were recorded on bare gold electrode and on gold electrodes coated with films of oligo-(R)-(−)-1a and oligo-(S)-(+)1a.

Figure 4. a) Enantiorecognition CV tests for the oligo-(S)-(+)1 a (a) and oligo-(R)-(−)-1a (b) film coated Au electrodes with (R)-3 and (S)-3 chiral redox probes (8 mm). c) Data also shown for the oligo-(S)-(−)-1a film coated Au electrode with the (±)-3 racemic redox probe. Potential scan rate: 50 mVs⁻¹.
Thank you for your attention