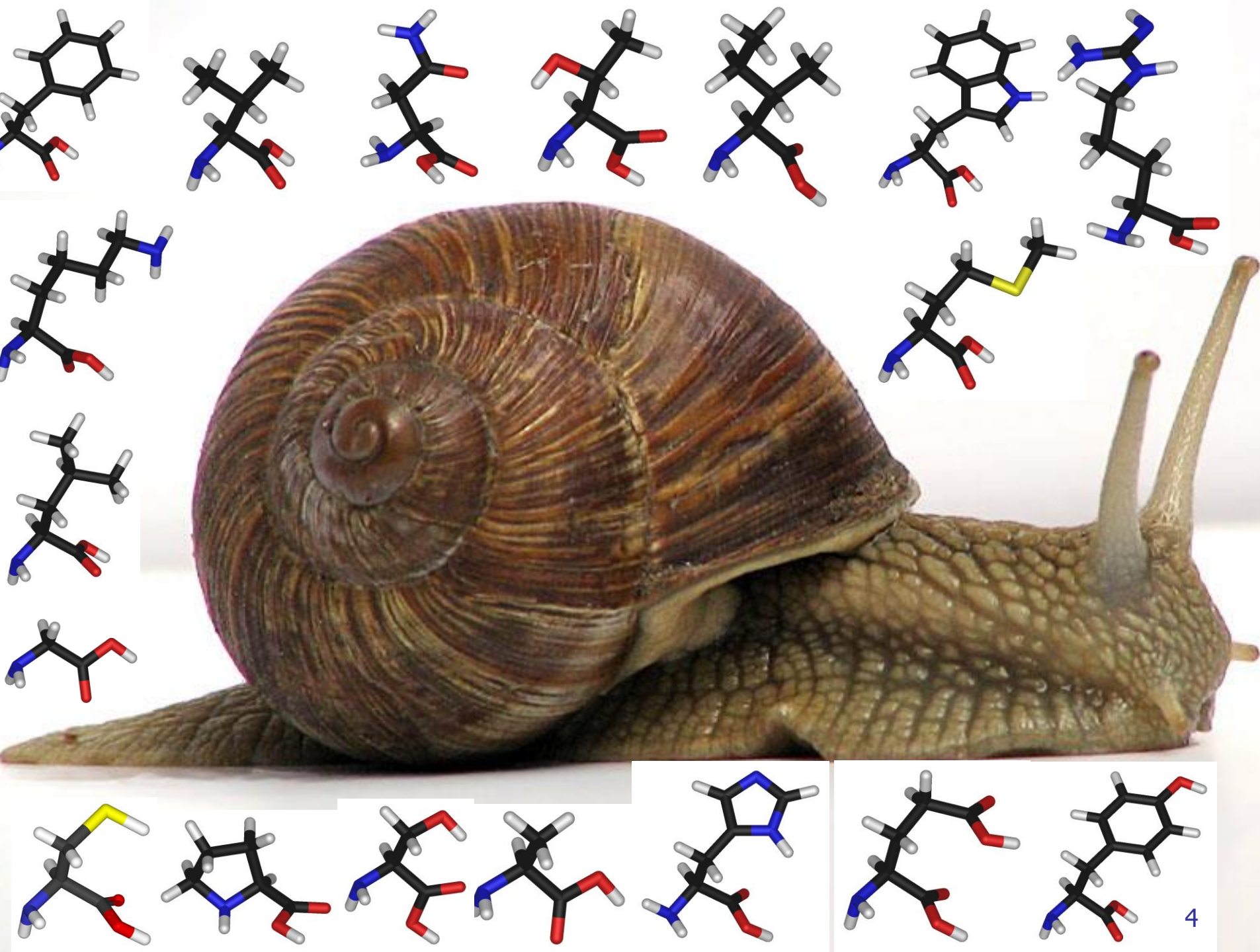




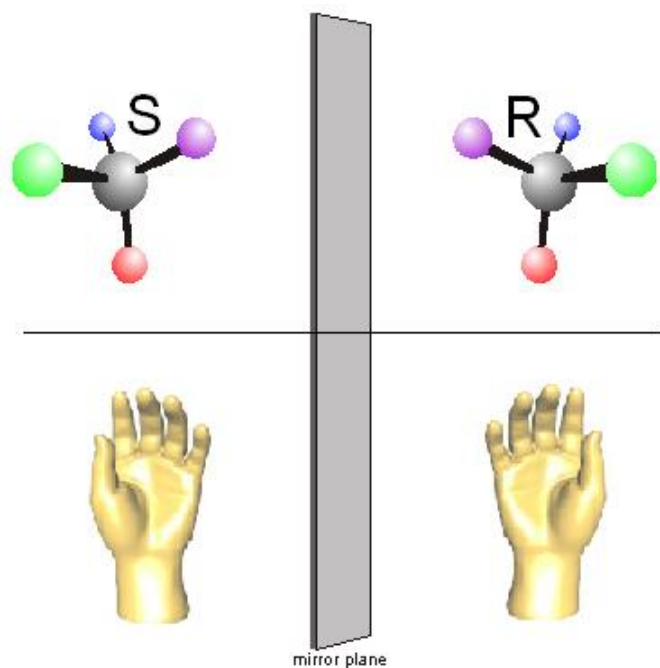
Jeremy - the left-coiled garden snail (died on October 11, 2017)







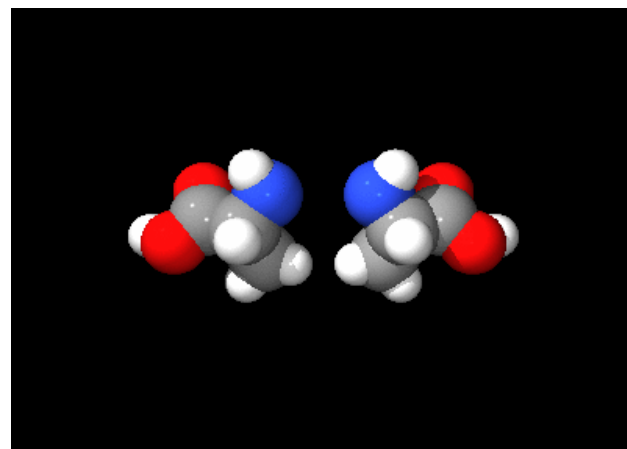
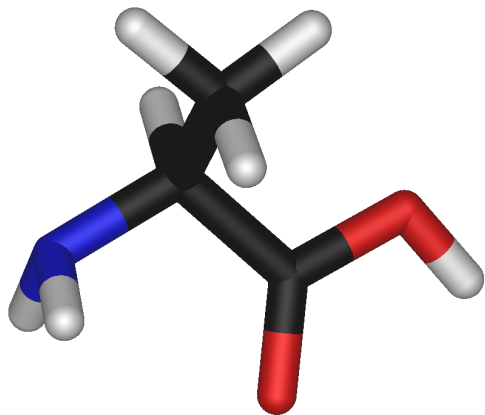
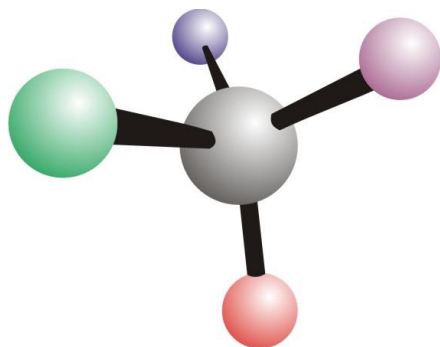
Definition of chirality



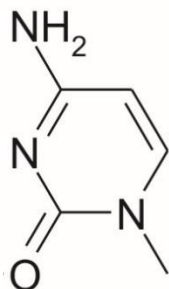
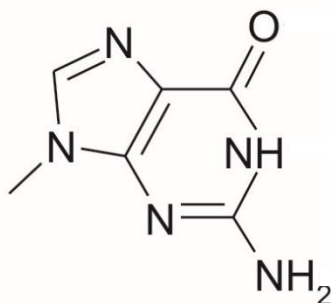
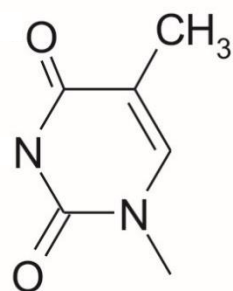
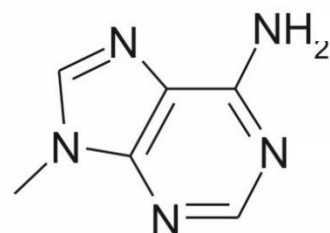
"I call any geometrical figure, or group of points, chiral, and say it has chirality, if its image in a plane mirror, ideally realized, cannot be brought to coincide with itself."

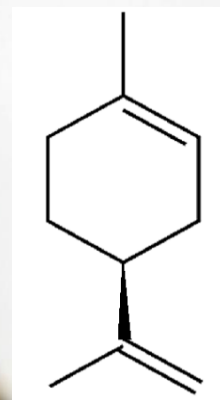
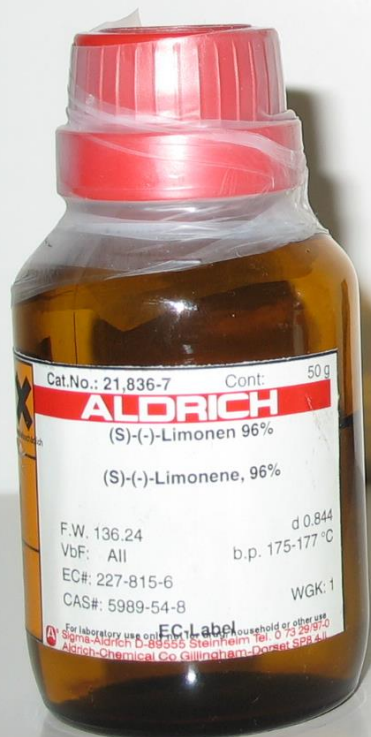
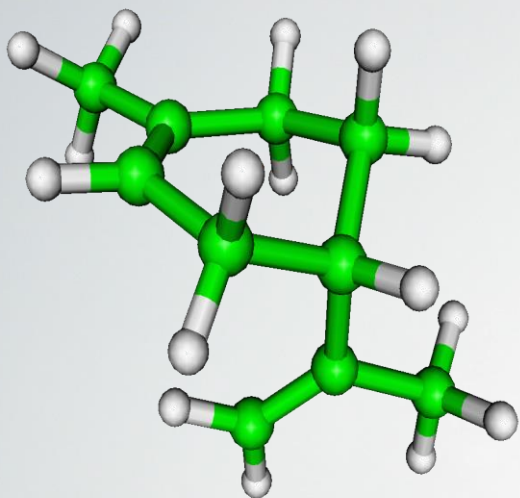
Lord Kelvin, 1904, Baltimore
Lectures on Molecular Dynamics
and the Wave Theory of Light

Examples of chiral objects in chemistry

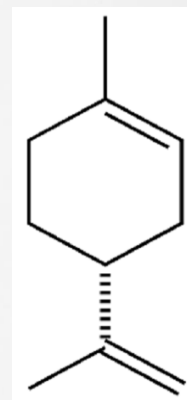


Examples of chiral objects in chemistry

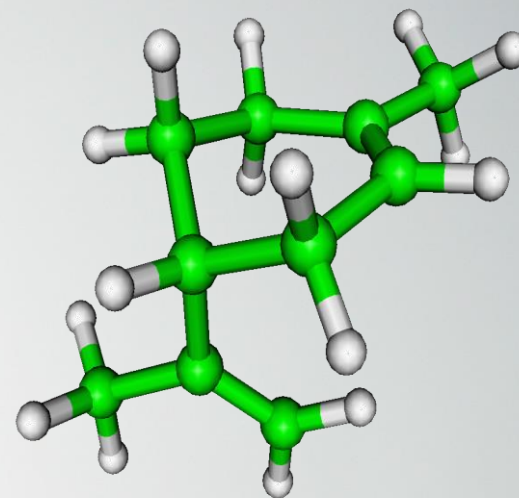




turpentine
oil



citrus
fruit





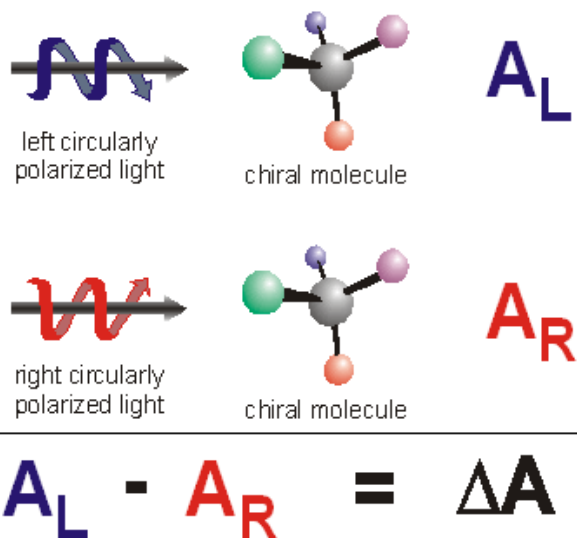
UNIVERSITY OF
CHEMISTRY AND TECHNOLOGY
PRAGUE

Athens: Introduction to Vibrational Spectroscopy

Vibrational circular dichroism I - principles

1 Circular dichroism

Definition of circular dichroism



$$\Delta A = A_L - A_R$$

$$\Delta A(\nu) = A_L(\nu) - A_R(\nu) \quad A = \epsilon c l$$

$$\Delta A/A \sim 10^{-3} - 10^{-5}$$

$$\Delta \epsilon(\nu) = \epsilon_L(\nu) - \epsilon_R(\nu)$$

Other chiroptical methods:

Optical rotation

$$\Phi \sim n_L - n_R$$

Optical rotation dispersion

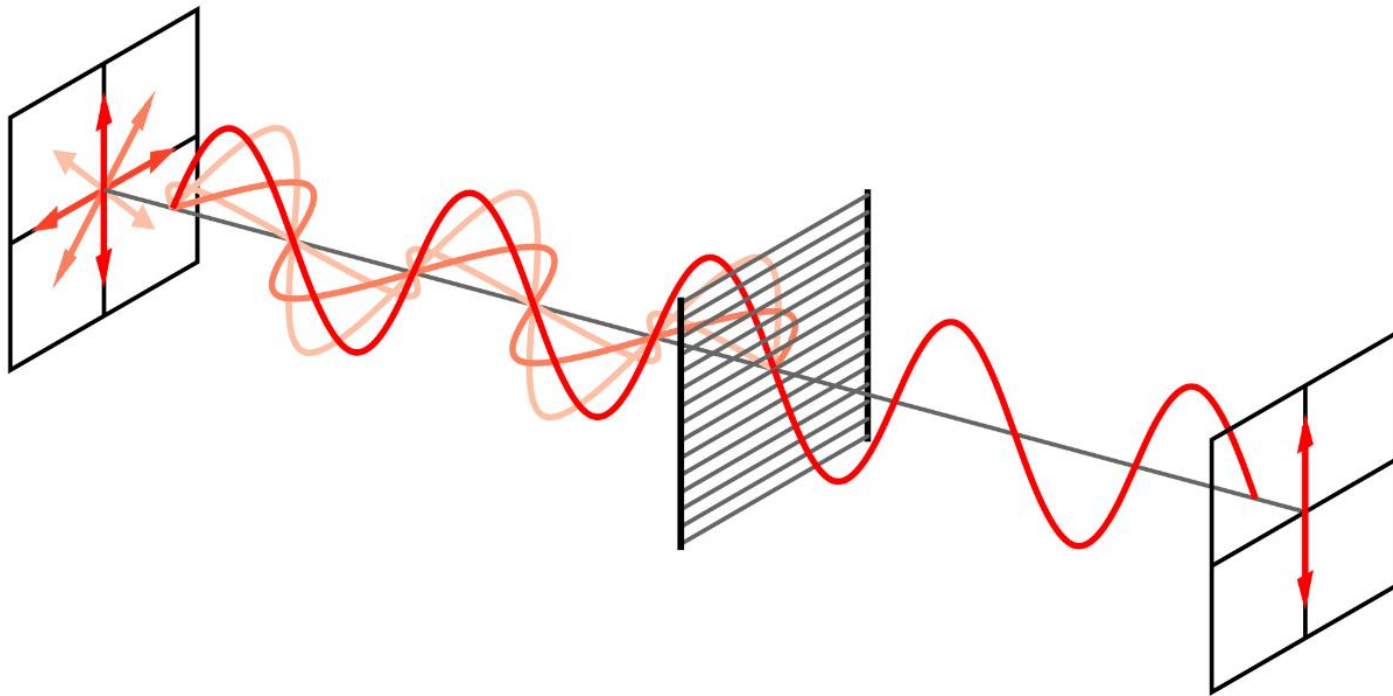
$$\Phi(\nu)$$

Raman optical activity (ROA)

$$\Delta I(\nu) \sim I_R(\nu) - I_L(\nu)$$

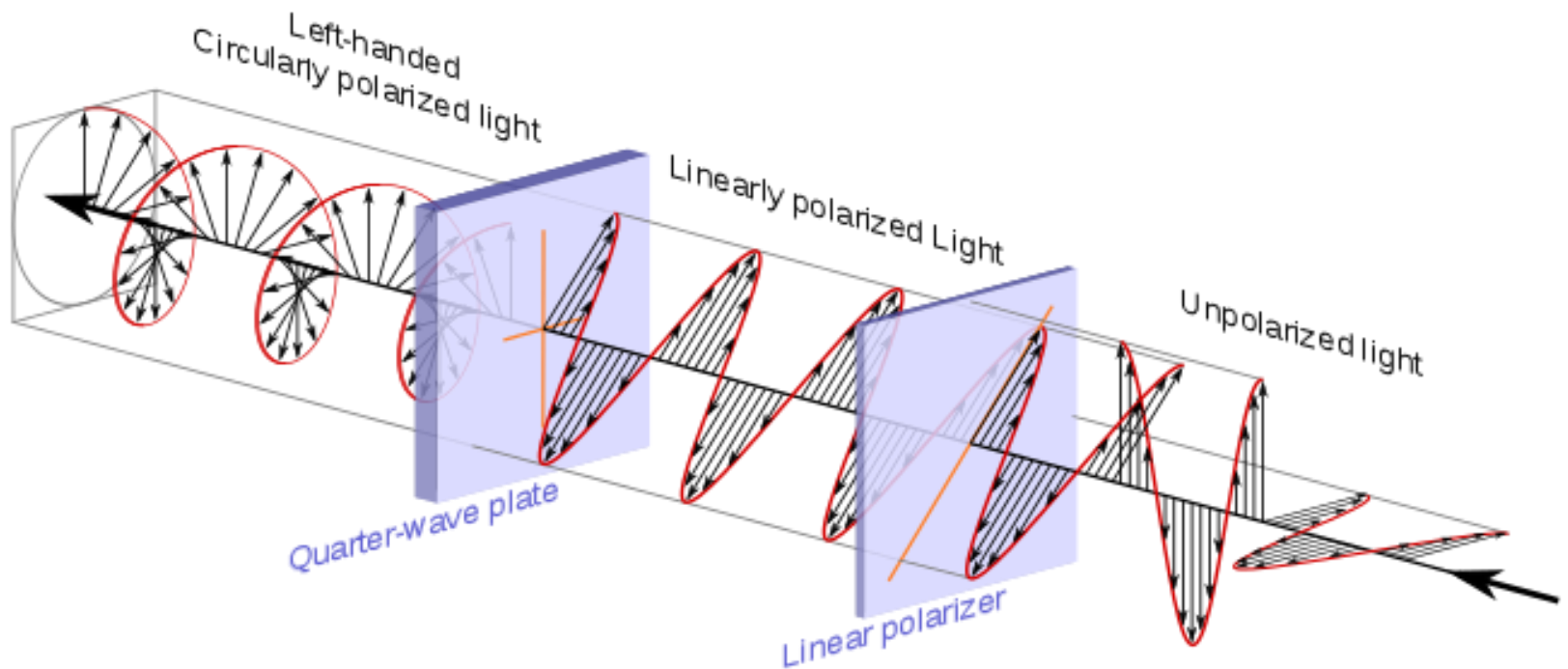
1 Circular dichroism

Unpolarized vs. Linearly polarized radiation (light)




1 Circular dichroism

Circularly polarized radiation (light)

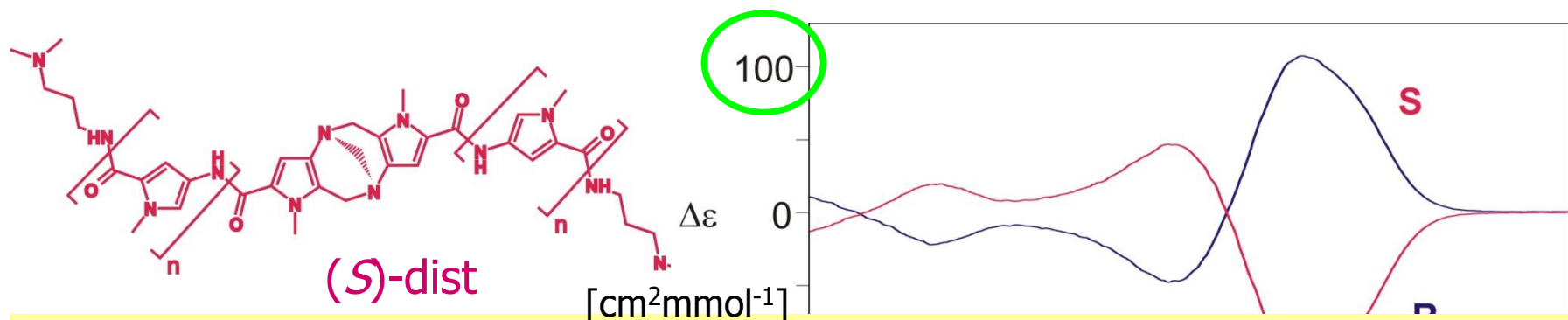


1 Circular dichroism

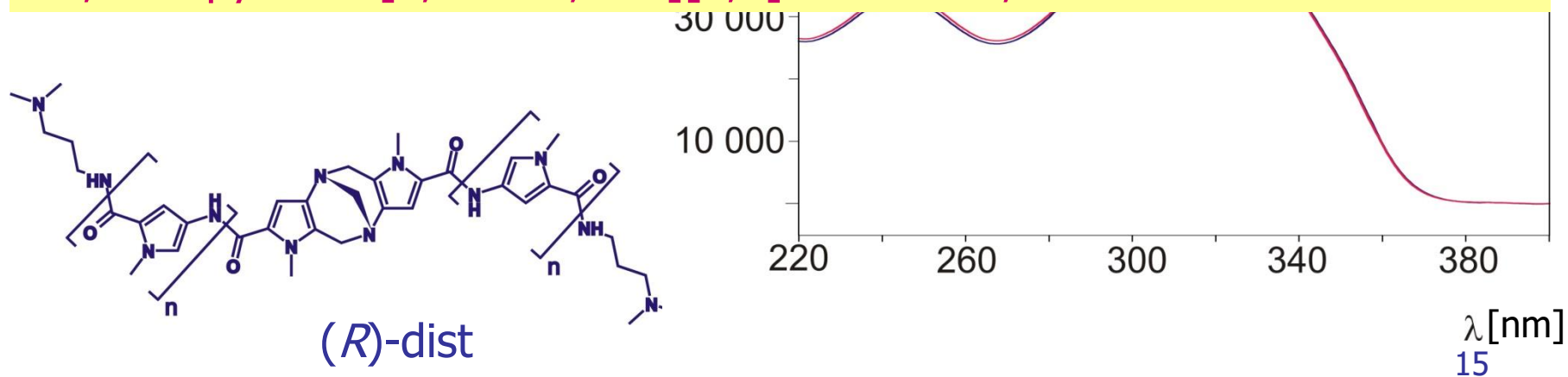
Wavelength	200 nm	400 nm	800 nm	1 μ m	10 μ m
Wavenumber/cm⁻¹	5 x 10 ⁴			1 x 10 ⁴	1 x 10 ³
Type of radiation					
Transitions	Electronic			Vibrational	
Spectroscopy	Electronic circular dichroism ECD			Vibrational circular dichroism VCD	
Signal observed for	UV-vis chromophores e.g. aromatic			<u>all</u> compounds	

1 Circular dichroism

Example of electronic circular dichroism spectra

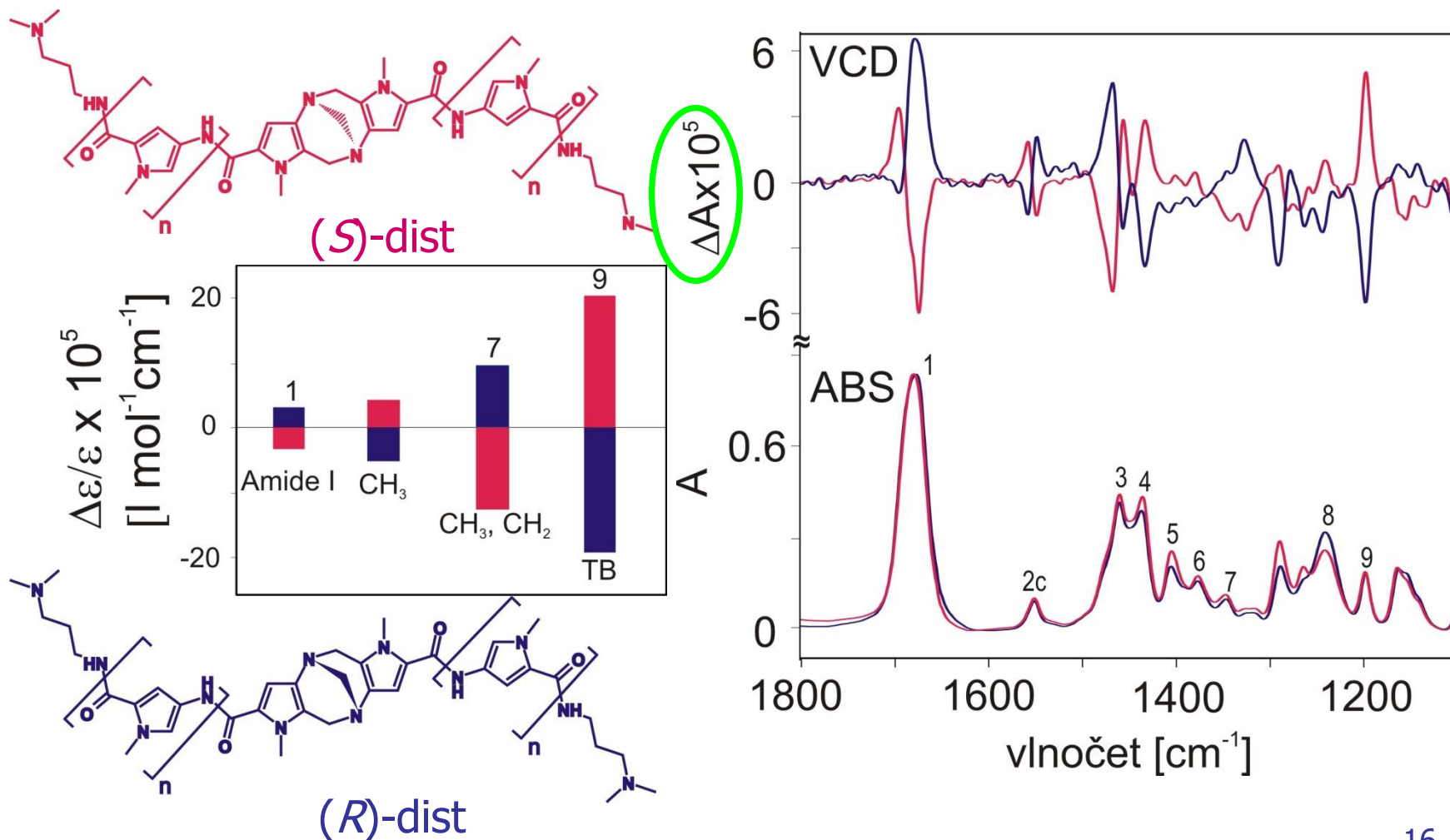


N,N'-bis(5-[\{5-[\{5-(3-dimethylaminopropyl)aminocarbonyl-1-methylpyrrol-3-yl\}aminocarbonyl]-1-methylpyrrol-3-yl\}aminocarbonyl]-1-methylpyrrol-3-yl)-(4*S*,9*S*)-4,9-methano-1,6-dimethyl-4,5,9,10-tetrahydro-1*H*,6*H*-dipyrrolo-[3,2-*b*:3',2'-*f*][1,5] diazocin-2,7-dicarboxamide



1 Circular dichroism

Example of vibrational circular dichroism spectra



1 Circular dichroism

*How is molecular structure encoded
in CD spectra?*

1 Circular dichroism

Spectroscopy – interaction of radiation with molecules

electromagnetic field – intensity of electric field ***E*** and magnetic induction ***B***

circularly polarized light – vectors



$$\hat{\mathbf{e}}_L = \frac{1}{\sqrt{2}} \{ (0, 1, i) \exp(i(kx - \omega t)) \}$$



$$\hat{\mathbf{e}}_R = \frac{1}{\sqrt{2}} \{ (0, 1, -i) \exp(i(kx - \omega t)) \}$$

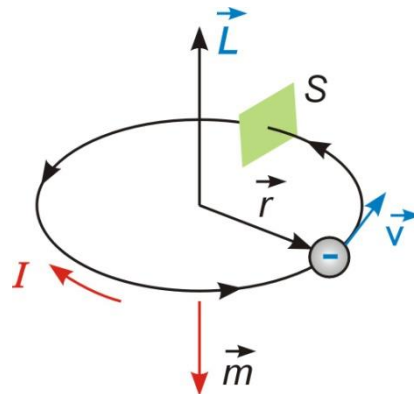
1 Circular dichroism

Spectroscopy – interaction of radiation with molecules

electric and magnetic properties of molecule given by
– electric a magnetic dipol moments

$$\boldsymbol{\mu} = e \sum_i \mathbf{r}_i,$$

$$\mathbf{m} = \frac{e}{2m_e} \sum_i \mathbf{r}_i \times \mathbf{p}_i$$



1 Circular dichroism

Interaction of electromagnetic field and a molecule described by quantum mechanics – interaction hamiltonian

$$\hat{H}^{\text{int}} = -\hat{\boldsymbol{\mu}} \bullet \mathbf{E} - \hat{\mathbf{m}} \bullet \mathbf{B} + \text{higher orders}$$

Absorption \sim dipole strength of transition

$$A \sim D^{if} = |\boldsymbol{\mu}^{fi}|^2$$

Circular dichroism (CD) \sim rotational strength of transition

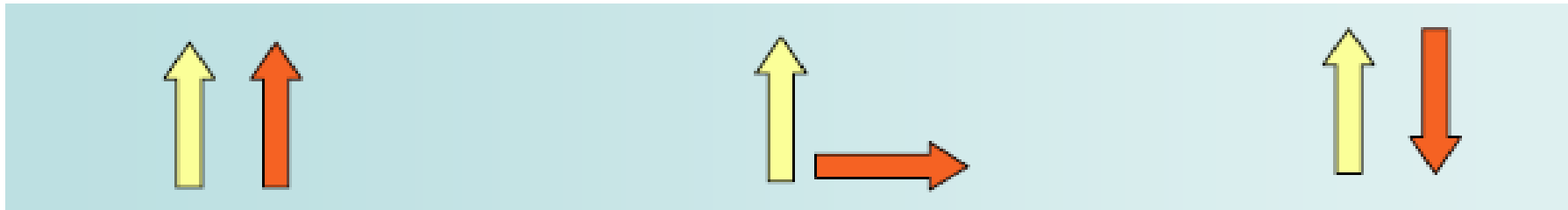
$$\Delta A = A_L - A_R$$

$$\Delta A \sim R^{if} = \text{Im}[\boldsymbol{\mu}^{fi} \bullet \mathbf{m}^{if}]$$

1 Circular dichroism

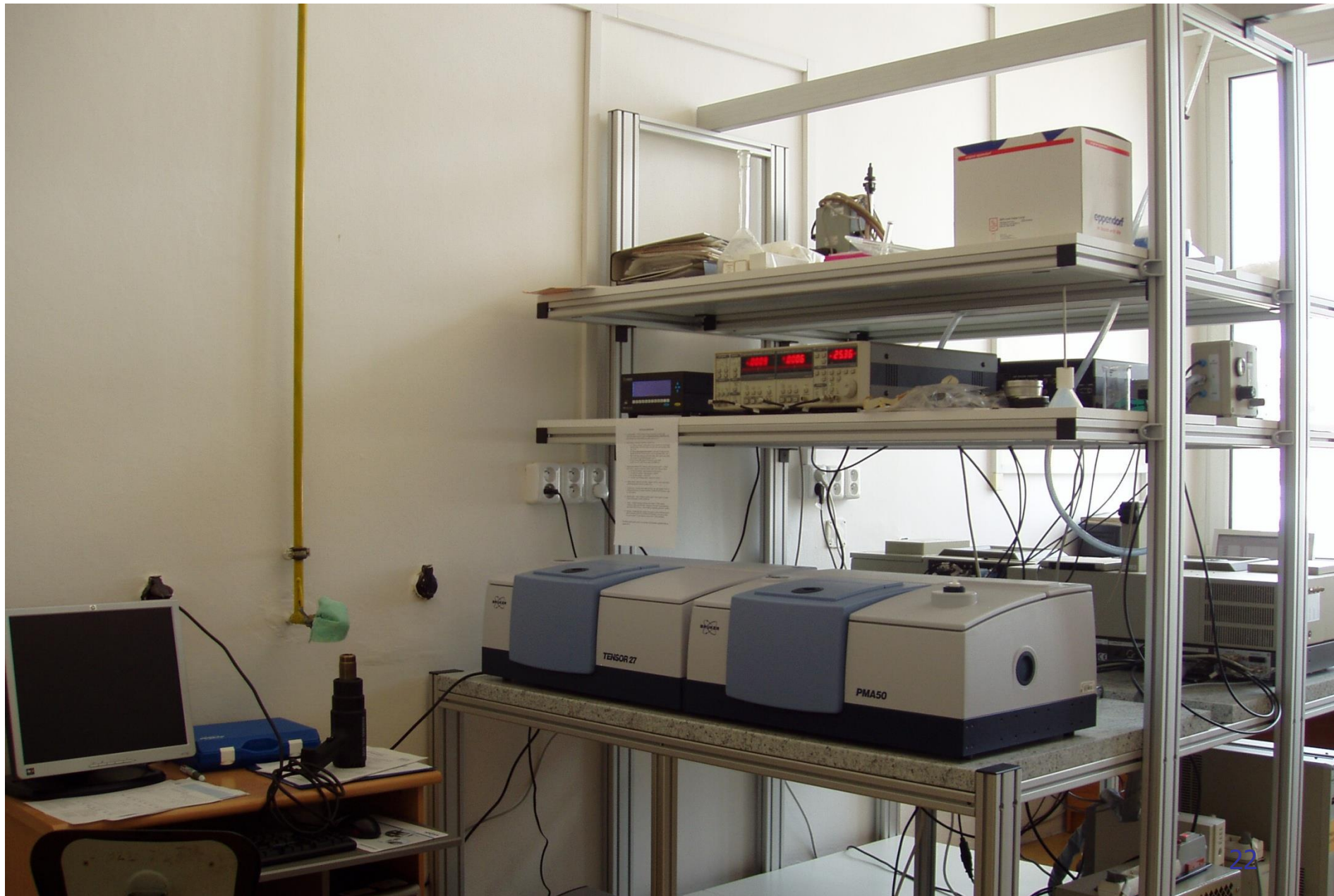
Circular dichroism (CD) \sim rotational strength of transition

$$\Delta A \sim R^{if} = \text{Im}[\boldsymbol{\mu}^{fi} \bullet \boldsymbol{m}^{if}]$$



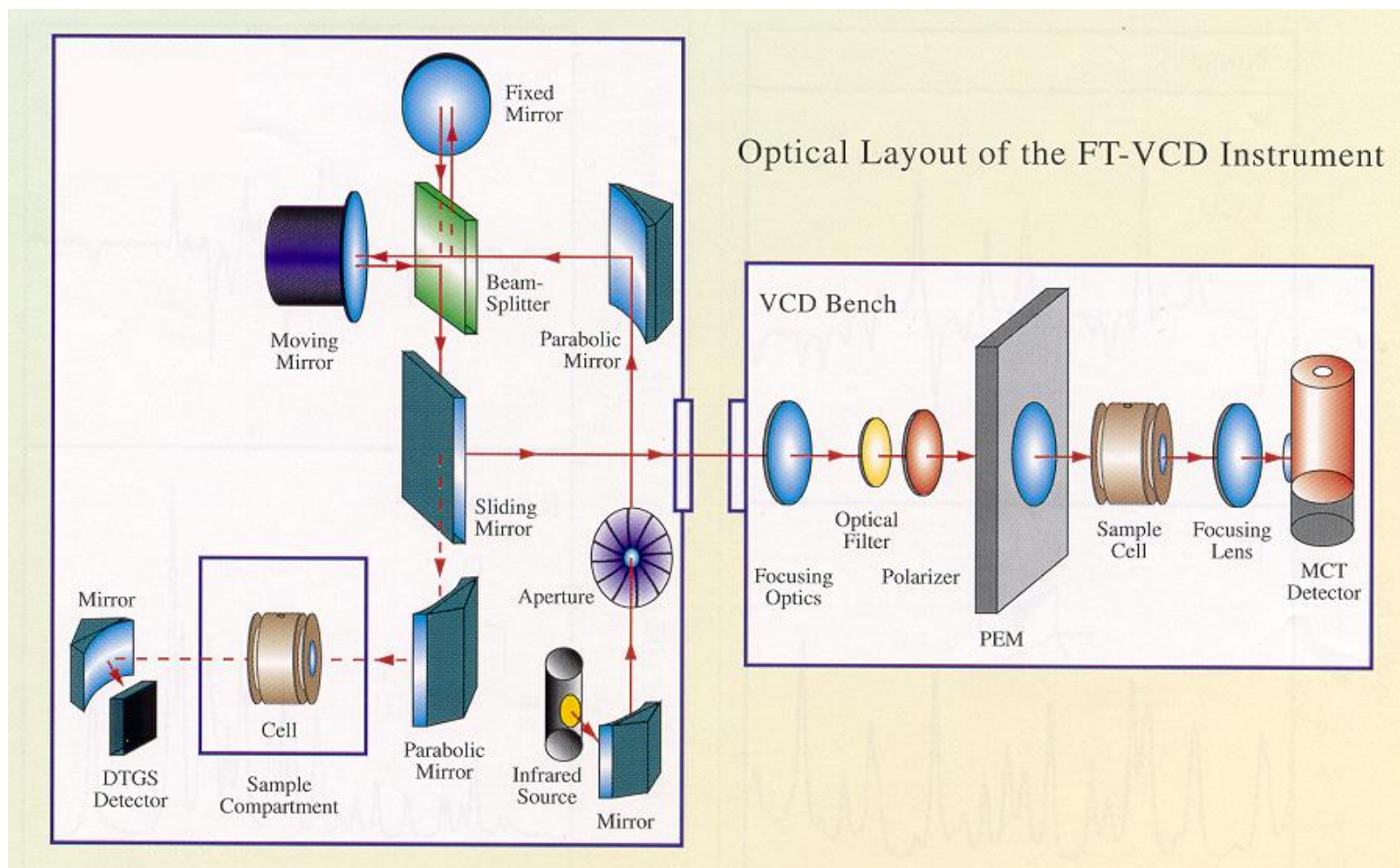
- = > structure gives the quantity and the sign of CD
- = > opposite sign of CD for the enantiomers in the whole spectral region, although unpolarized absorption does not differentiate them

2 Experimental



2 Experimental

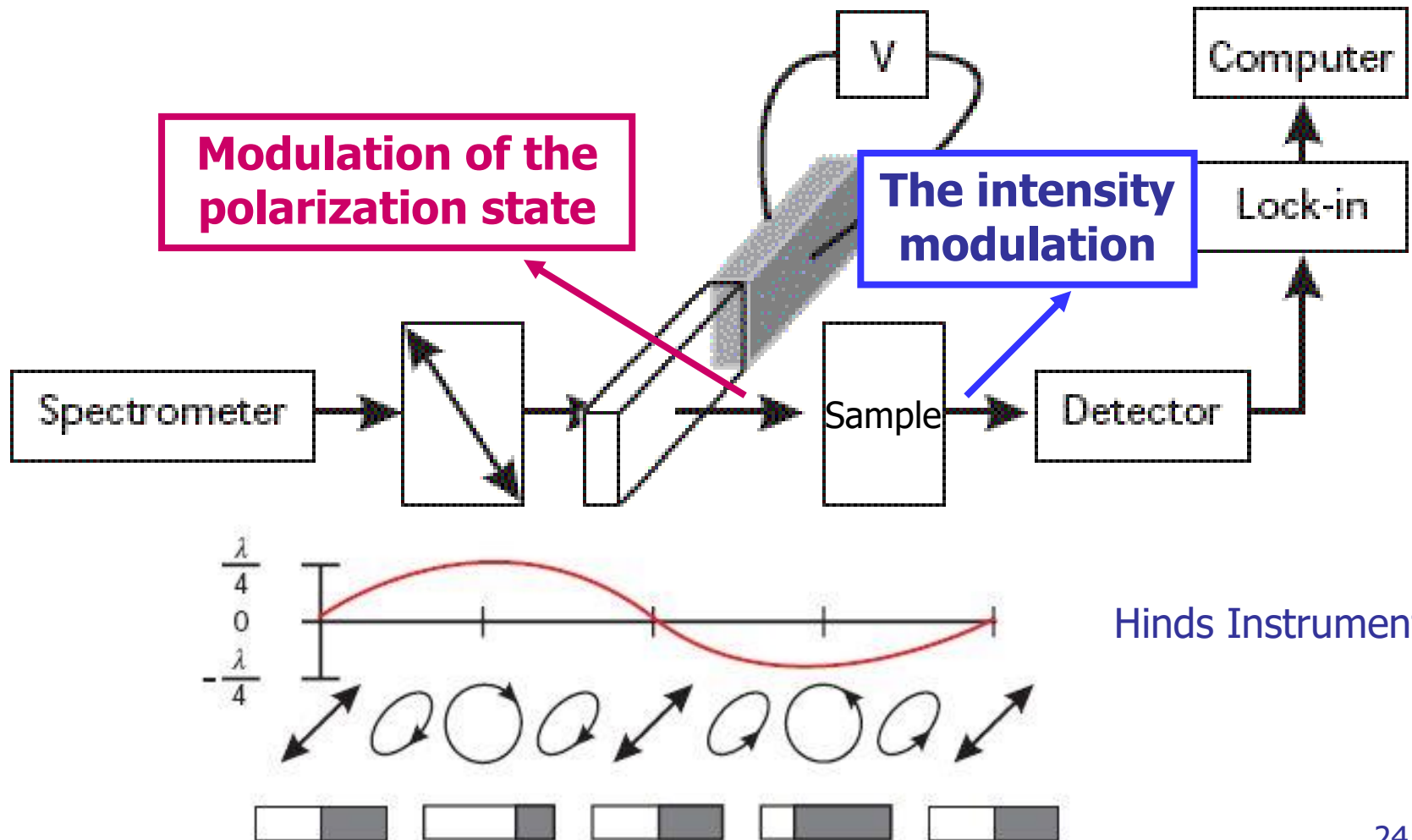
Vibrational circular dichroism (VCD)



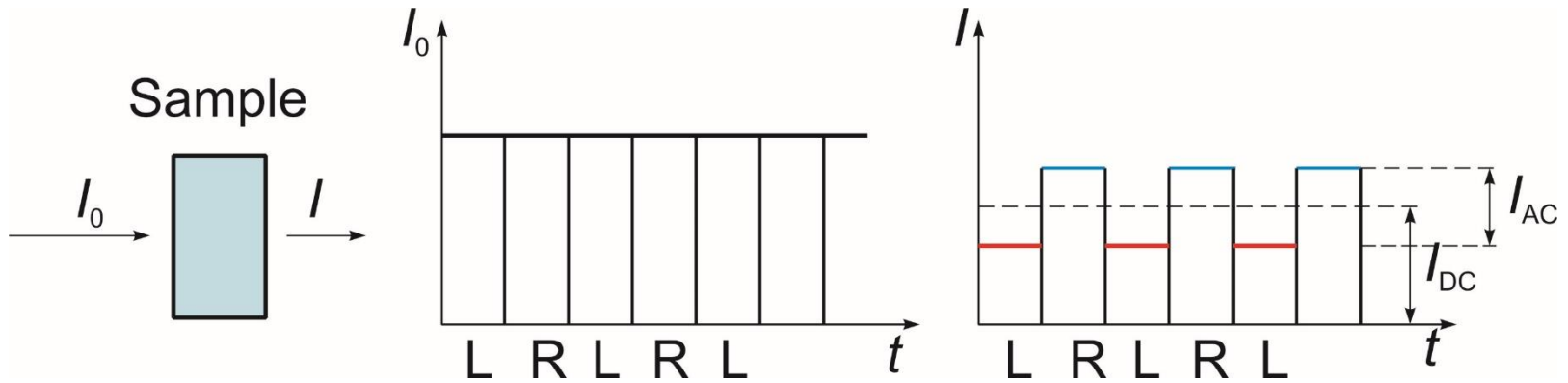
Nafie L. A.: *Appl. Spectrosc.* **1996**, 50, 14A.

2 Experimental

The crucial part of CD spectrometer
– photoelastic modulator (PEM)

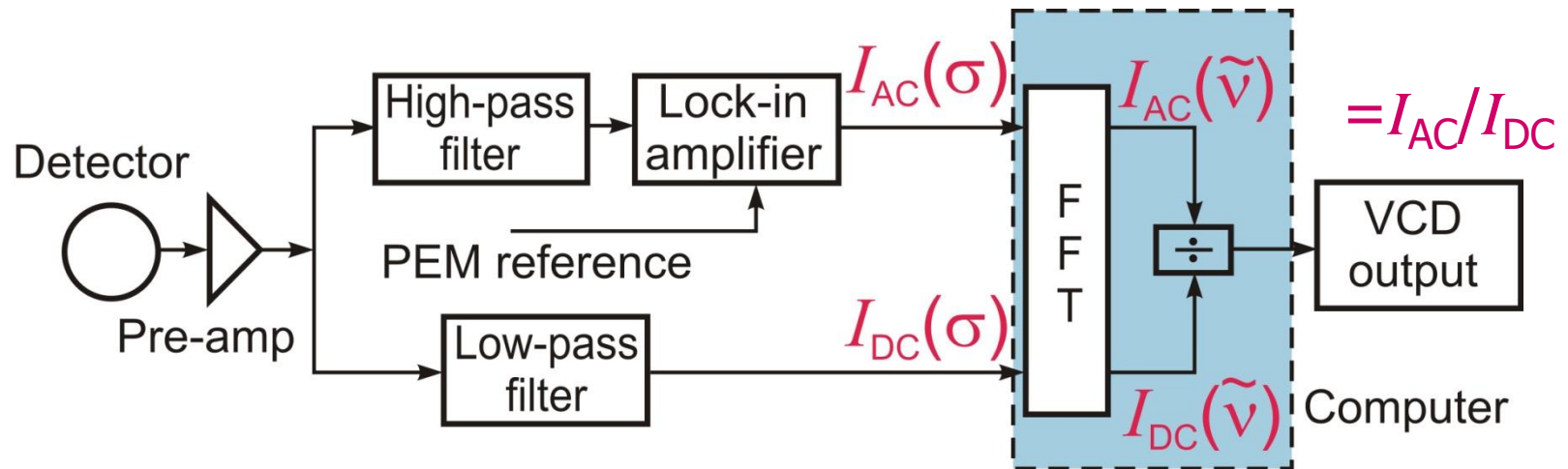


2 Experimental



$$A_L - A_R \sim \frac{I_{AC}}{I_{DC}}$$

2 Experimental



2 Experimental

- Experimental conditions for VCD spectroscopy
 - Spectral limitation given
 - by the material of all optical elements (PEM etc.)
 - sensitivity of detector
 - 900-2000 cm^{-1} : MCT, cooled by liquid nitrogen
 - 2000-4000 cm^{-1} : MCT, thermodynamically cooled or InSb cooled by liquid nitrogen
 - 4000-6000 cm^{-1} : InGaAs, room temperature
 - 5000-9000 cm^{-1} : Ge, room temperature
 - solvent
 - **the most popular region: 2000 – 800 cm^{-1}**

2 Experimental

- IR solvents appropriate for VCD spectroscopy in the mid IR region and their spectral windows

Solvent	Spectral window (cm ⁻¹)	Solvent	Spectral window (cm ⁻¹)
CCl ₄	2000–850	DMSO- <i>d</i> ₆	2000–1100; 970–700
CS ₂	2000–1640; 1350–700	Methanol- <i>d</i> ₄	2000–1200
CHCl ₃	2000–1260; 1175–700	H ₂ O ^a	2000–1770; 1525–1000
CDCl ₃	2000–975	D ₂ O	2000–1300; 1100–800 ^a
Propanol	2000–1500	trifluorethanol	2000–1500

^aonly when a short pathlength < 6 μm and higher concentrations are used.

2 Experimental

- Experimental conditions for VCD spectroscopy
 - Dynamic range: $A \sim 0.1 - 1$, optimum $0.4 - 0.6$
 - Combination of appropriate sample concentration, the cell thickness and appropriate solvent
 - Typical concentration $0.05 - 1 \text{ mol l}^{-1}$
 - Typical volume $50 - 100 \mu\text{l}$
 - Typical mass of sample $1 - 15 \text{ mg}$



3 Processing of circular dichroism spectra

- Zero line correction
 - the **zero line distortion** may be comparable in size to the sample signals and may cause artifacts, the sources are:
 - Birefringence in the optical materials (optical lenses, filters, cells and other windows)
 - Reflections
 - Sample absorption: in the region of absorption band, anomalous dispersion takes place that may distort the equilibrium of the responses to left and right circularly polarized light, primarily in the case of a narrow sharp absorption band

3 Processing of circular dichroism spectra

- Corrected spectrum can be obtained when both enantiomers are available:
 - for the same concentrations of the both enantiomers R and S : $A_S(\nu) = A_R(\nu)$ $\Delta A_S(\nu) = -\Delta A_R(\nu)$
 - experimental spectra of the both enantiomers contain the same distortion $D(\nu)$:
$$\Delta A_R^{\text{exp}}(\nu) = \Delta A_R(\nu) + D(\nu)$$
$$\Delta A_S^{\text{exp}}(\nu) = \Delta A_S(\nu) + D(\nu)$$
 - summation gives twofold distortion and difference twofold spectrum of single enantiomer:

$$N(\nu) = \frac{1}{2} \left(\Delta A_S^{\text{exp}}(\nu) + \Delta A_R^{\text{exp}}(\nu) \right) \quad \Delta A_S(\nu) = \frac{1}{2} \left(\Delta A_S^{\text{exp}}(\nu) - \Delta A_R^{\text{exp}}(\nu) \right)$$

4 Circular dichroism and molecular structure

- 1 Structural methods with high (atomic) resolution
 - X-ray, neutron diffraction
 - NMR
 - rotational and rotational-vibrational spectroscopy (for small molecules in the gas state only)
 - Numerical methods
- 2 Scanning and transmission microscopy

4 Circular dichroism and molecular structure

3 Structural methods with low resolution – optical spectroscopy

spectral region and further properties of electromagnetic radiation implicate information that can be obtained

- UV-VIS absorption and fluorescence are intensity oriented
- IR absorption a Raman spectroscopy frequency oriented
- CD (ECD or VCD) contains the structural information in the frequency, intensity and the shape of signal for all states, under different physico-chemical conditions, fast, less expensive

4 Circular dichroism and molecular structure

Vibrational circular dichroism (VCD) – advantages and disadvantages

- higher spectral resolution than UV-VIS
- additional resolution by isotopic substitution
- all molecules possess IR spectrum, no special chromospheres needed
- characteristic vibrations are localized in molecule
- very good theoretical background

4 Circular dichroism and molecular structure

Vibrational circular dichroism (VCD) – advantages and disadvantages

- only for chiral objects
- high concentrations needed (single measurement – 2.5 mg of sample)
- weak signals, 10^{-4} - 10^{-5} A
- limited IR transmission of solvent, deuterated solvents

5 Utilization of circular dichroism

Circular dichroism

- enantiomeric purity
- absolute configuration of small- and middle-sized molecules
- structure of peptides, proteins, oligonucleotides and DNA
- biologically interesting interactions
- structural studies of supramolecular interactions
- transcription of chiral information
- molecular recognition