



Magneto-chiral anisotropy; what has been done, what could be done

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LNCMI



“Il n'y a pas de choses simples, mais il y a une manière simple de voir les choses.”

Paul Valéry

Summary

- Symmetry and all that

- Magneto-chiral effects

- history

- in optics

- in transport

- in mechanics

- Summary and conclusion

Symmetry

Continuous symmetries (Noether theorem):

Translational time invariance $t \rightarrow t + \Delta t \Leftrightarrow$ Energy conservation

Translational invariance $\mathbf{r} \rightarrow \mathbf{r} + \Delta \mathbf{r} \Leftrightarrow$ Momentum conservation

Rotational invariance $\phi \rightarrow \phi + \Delta \phi \Leftrightarrow$ Angular momentum cons.

CPT symmetries:

Charge conjugation C: $q \rightarrow -q$ (matter \rightarrow anti-matter)

Parity P: $\mathbf{r} \rightarrow -\mathbf{r}$ (\sim take mirror image)

Time reversal T: $t \rightarrow -t$ (\sim play movie backwards)

We will **assume** physics to be invariant under C and P and T;
valid for: electrodynamics and (quantum) mechanics,
invalid for: nuclear processes (only **CPT** invariance)

Recipe for the use of C-P-T symmetries:

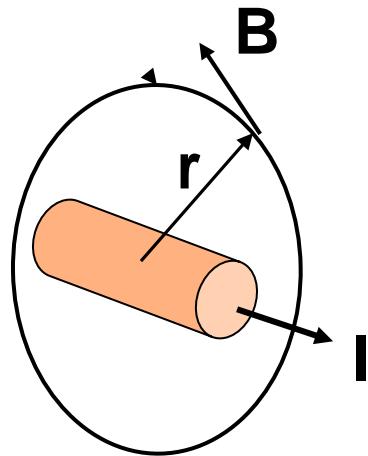
If an effect is described by $\vec{X} = f(\vec{Y}, z, t, \dots)$ then the r.h.s. and l.h.s. should transform identically separately under C and P and T

Note:

- 1) A symmetry argument does not say whether an effect exists, but only if it is forbidden or not
- 2) CPT symmetry arguments only apply to deterministic descriptions

The CPT symmetry of a physical quantity; example of the magnetic field

$$\left. \begin{aligned} \mathbf{B} &= \frac{1}{4\pi\epsilon_0} \frac{2\mathbf{I} \times \mathbf{r}}{r^2} \\ \mathbf{I} &= qN \frac{\partial \mathbf{r}}{\partial t} \end{aligned} \right\} \quad \mathbf{B} = \frac{qN}{4\pi\epsilon_0} \frac{2 \frac{\partial \mathbf{r}}{\partial t} \times \mathbf{r}}{r^2}$$



Parity reversal P: $\mathbf{r} \rightarrow -\mathbf{r}$, $t \rightarrow t$, $q \rightarrow q$ so $\mathbf{B} \rightarrow \mathbf{B}$

Charge conjugation C: $\mathbf{r} \rightarrow \mathbf{r}$, $t \rightarrow t$, $q \rightarrow -q$ so $\mathbf{B} \rightarrow -\mathbf{B}$

Time reversal T: $\mathbf{r} \rightarrow \mathbf{r}$, $t \rightarrow -t$, $q \rightarrow q$ so $\mathbf{B} \rightarrow -\mathbf{B}$

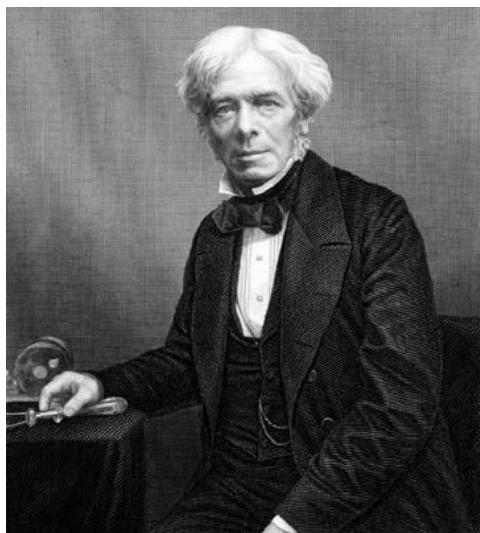
Magnetic field is a time-odd pseudo-vector



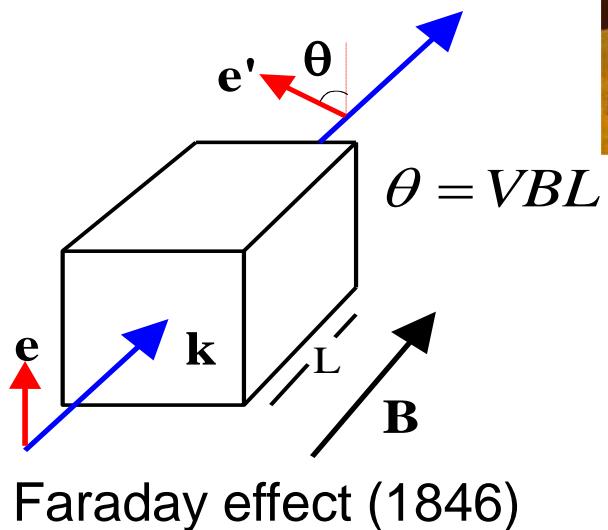
CPT properties of common physical quantities

		C	P	T
electrical current	I	-	-	-
electric field	E	-	-	+
magnetic field	B	-	+	-
voltage	V	-	+	+
momentum	p	+	-	-
force	F	+	-	+
angular momentum	L	+	+	-
mass	m	+	+	+

Application to magneto-optics



Michael Faraday



The coupling between magnetic field and light was the key element in the development of the theory of electromagnetism.

CPT symmetry and magneto-optics

Perturbation approach:

$$\mathbf{P}^\omega(\mathbf{B}_0) = \chi(\omega, \mathbf{B}_0) \mathbf{E}^\omega = \chi(\omega) \mathbf{E}^\omega + f_1(\mathbf{B}_0, \mathbf{E}^\omega) + f_2(\mathbf{B}_0, \mathbf{B}_0, \mathbf{E}^\omega) + \dots$$

Symmetry:

	C	P	T
P	-	-	+
B	-	+	-
E	-	-	+

Simplest symmetry allowed form from P and T invariance:

$$\mathbf{P}^\omega(\mathbf{B}_0) = \chi(\omega) \mathbf{E}^\omega + \chi_1 \frac{\partial \mathbf{E}^\omega}{\partial t} \times \mathbf{B}_0 + \chi_2 (\mathbf{B}_0 \cdot \mathbf{B}_0) \mathbf{E}^\omega + \chi_3 (\mathbf{B}_0 \cdot \mathbf{E}^\omega) \mathbf{B}_0 + \dots$$

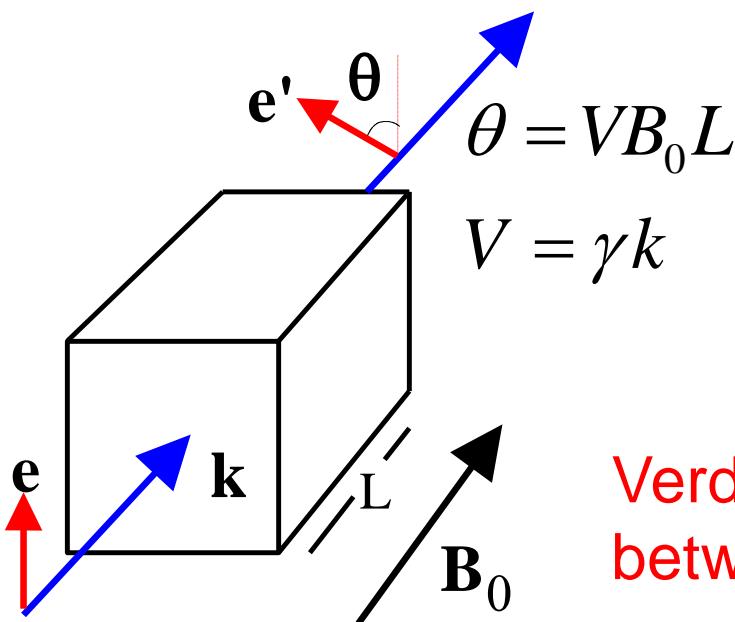
$$= \chi(\omega) \mathbf{E}^\omega + i\omega \chi_1 \mathbf{B}_0 \times \mathbf{E}^\omega + O(B_0^2) \quad \text{Levi-Civitta}$$

Dielectric constant: $\varepsilon_{ij}(\omega, \mathbf{B}_0) = 1 + 4\pi\chi_{ij} = \varepsilon_{ij}(\omega) + i\gamma(\omega) \overset{\downarrow}{e}_{ijk} B_{0k}$

C invariance: $\gamma(\omega)$ odd under C

**Maxwell:**

$$\nabla \times \nabla \times \mathbf{E}^\omega = -\frac{\epsilon}{c} \frac{\partial^2 \mathbf{E}^\omega}{\partial t^2}$$

Faraday geometry: $\mathbf{k} \uparrow\uparrow \mathbf{B}_0 \equiv \mathbf{z}$ **Ansatz:** $\mathbf{E}^\omega = E^\omega(z) \exp(i\omega t - ikz) \mathbf{x}$ **Solution:** $\mathbf{E}^\omega(z) = E^\omega \exp(i\omega t - ikz) \{ \cos(\Delta kz) \mathbf{x} + \sin(\Delta kz) \mathbf{y} \}$
with $\Delta k \equiv \gamma kB$ 

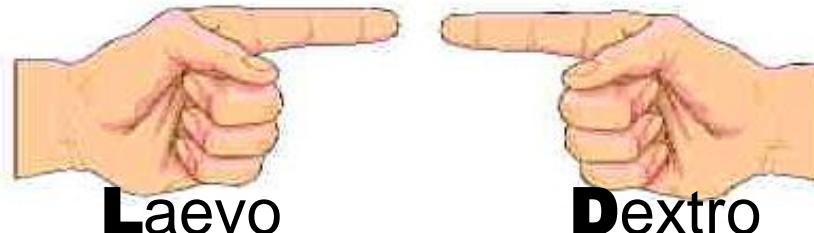
Faraday effect (1846)

V = Verdet constant

Verdet constant is the only linear coupling
between light and magnetic field in matter.

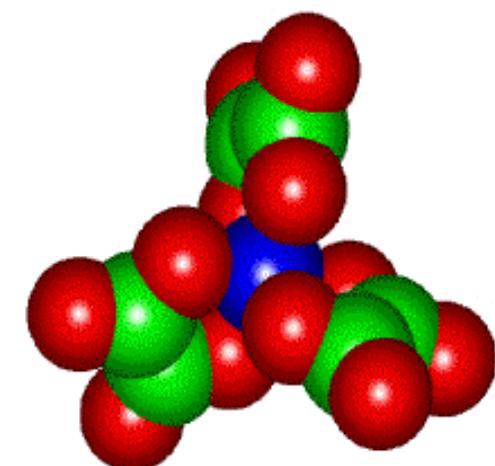
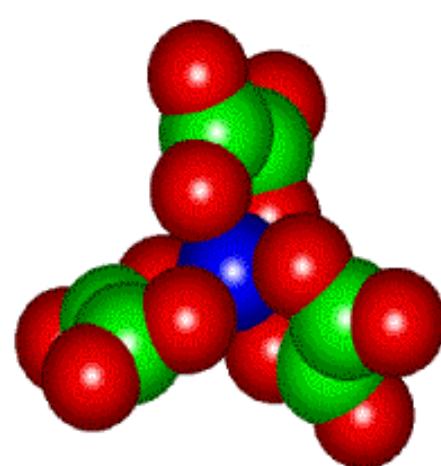
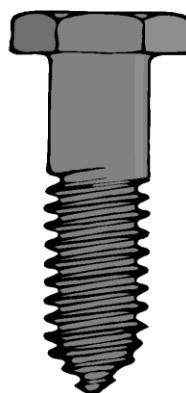
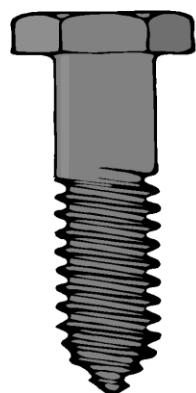
Chirality

(χειρ = hand)



Definition: A system is called *chiral* when it exists in two forms (enantiomers) that can only be interconverted by a parity operation

Examples:



Note: Biochemistry is ‘homochiral’, so chirality is vital

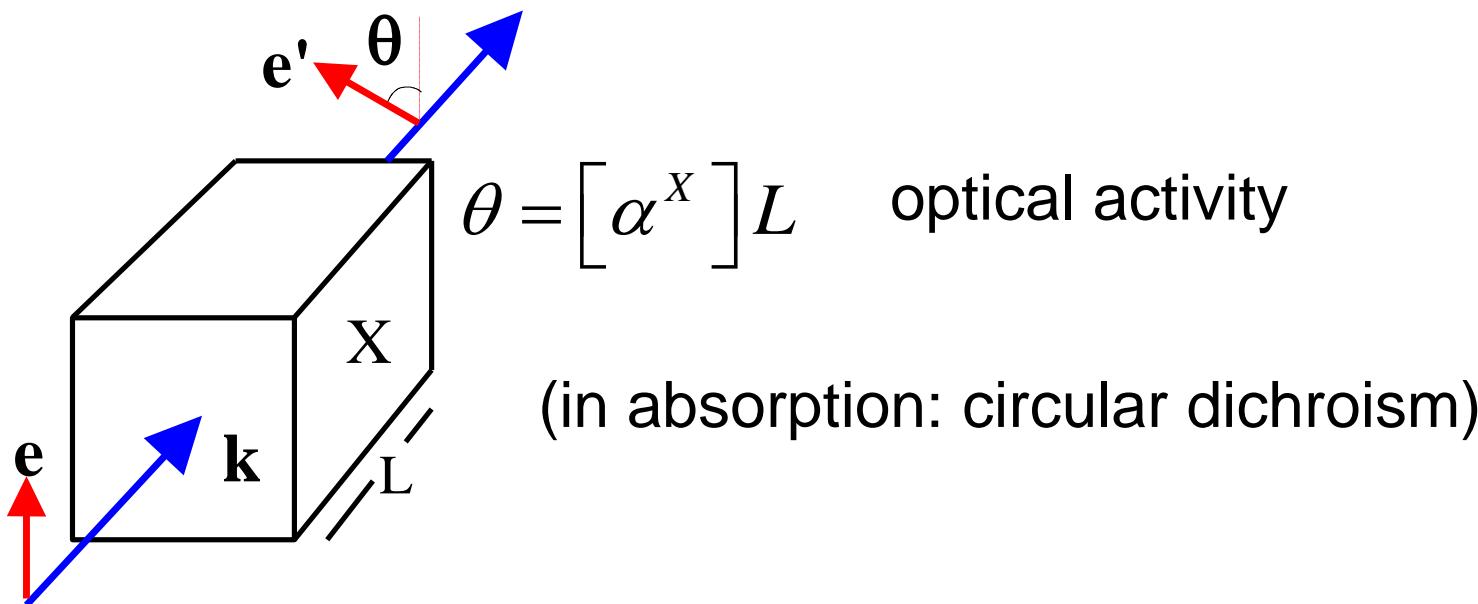
Optical properties of chiral systems

spatial dispersion (non-local optical response):

$$\varepsilon(\omega, k) = \varepsilon(\omega) + \alpha_1(\omega)k + \alpha_2(\omega)k^2 + \dots$$

in non-chiral systems: $\alpha_1(\omega) \equiv 0$

in chiral systems: $\alpha_1(\omega) \neq 0$, $\alpha_1^D(\omega) = -\alpha_1^L(\omega)$





Magneto-chiral effect, some history

Pasteur tried crystallisation in magnetic field to select chirality (1855)

Curie established the symmetry of chirality and magnetic field (1894)

Groenewege; the first (implicit) prediction of the magneto-chiral effect in optical properties (1962)

Baranova (1977), Wagnière (1982) and Barron (1984): theory of optical magneto-chiral effect

Magneto-optical properties of chiral systems

Breaking of parity symmetry by chirality leads to **optical activity**.

Breaking of time reversal symmetry by a magnetic field leads to the **Faraday effect**.

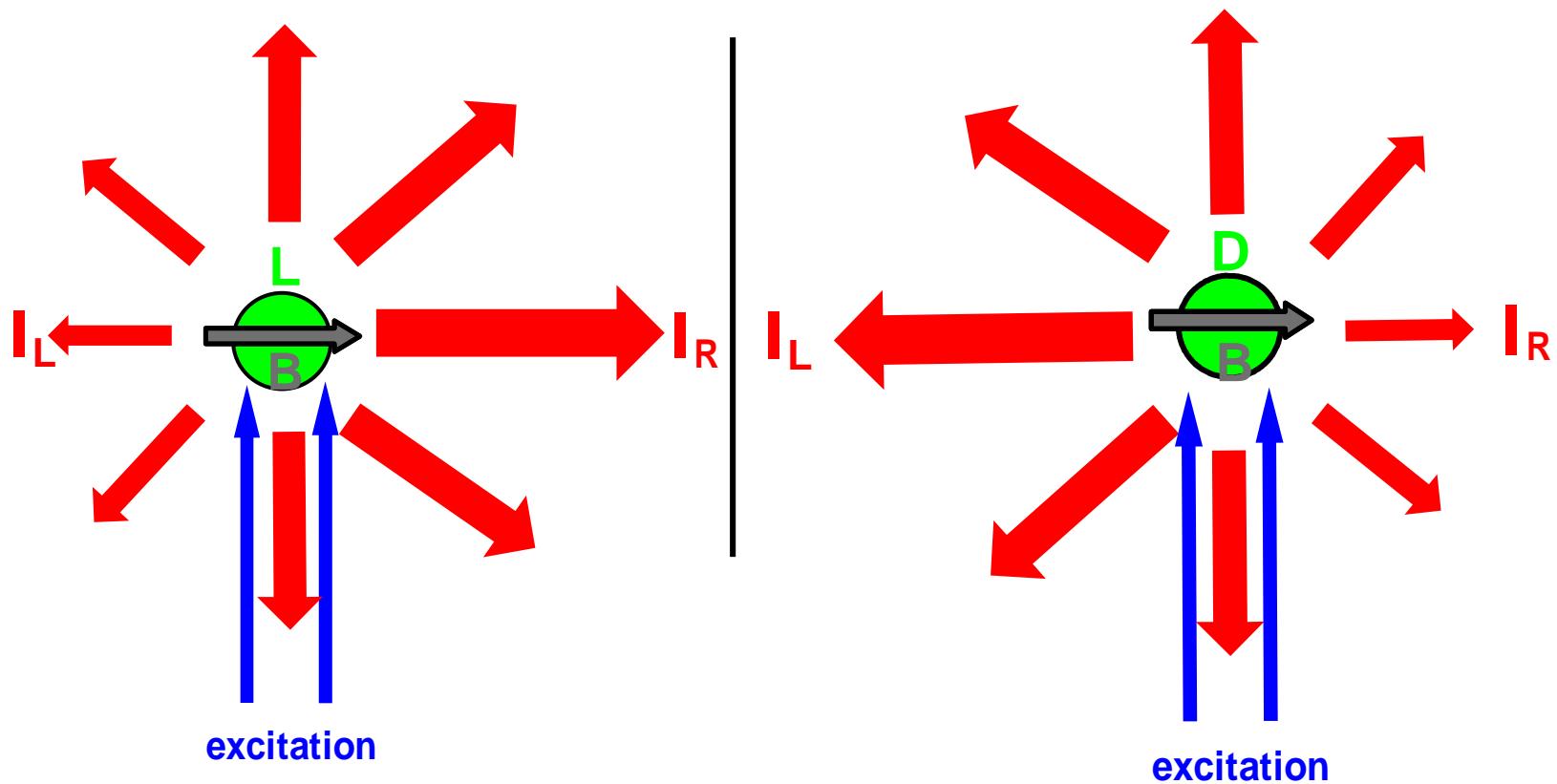
Breaking both symmetries leads to an **additional** new effect: **magnetochiral anisotropy**.

symmetry allowed expansion of dielectric constant for CPL:

$$\varepsilon(\omega, \mathbf{k}, \mathbf{B})_{\pm}^{D/L} = \varepsilon(\omega) \pm \alpha(\omega)^{D/L} k \pm \gamma(\omega) B + \Omega(\omega)^{D/L} \mathbf{k} \cdot \mathbf{B}$$

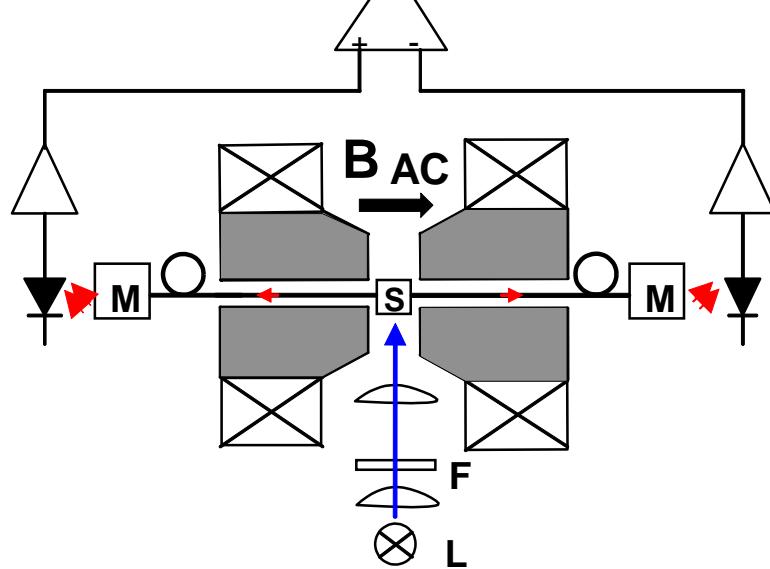
- dependent on relative orientation of light and field
- independent of polarization
- enantioselective: $\Omega^D = -\Omega^L$

MChA in luminescence



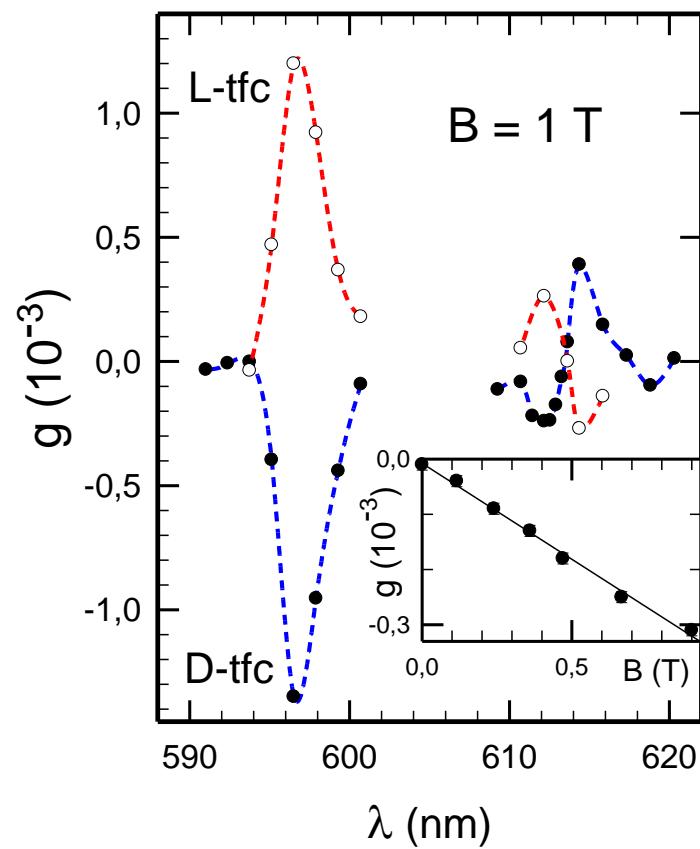
Observation of MChA in luminescence

$$\text{LA} \rightarrow I(\mathbf{B} \uparrow\uparrow \mathbf{k}) - I(\mathbf{B} \uparrow\downarrow \mathbf{k}) \propto \text{Im} \Omega$$



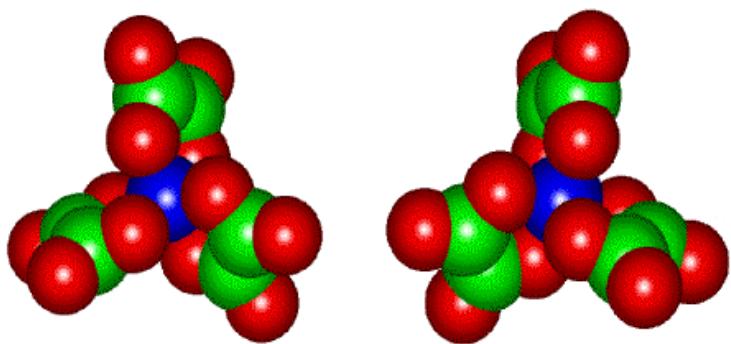
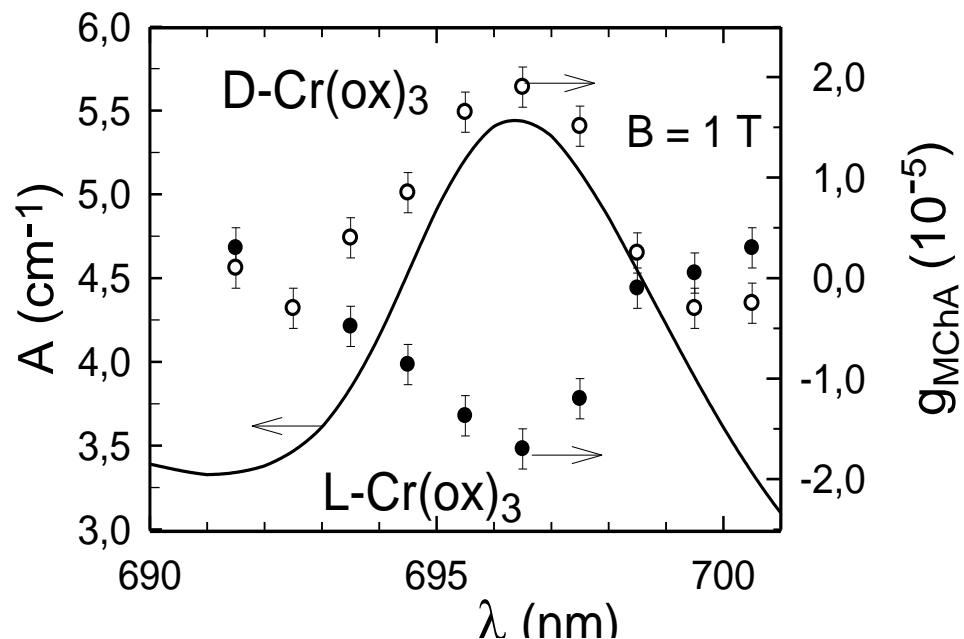
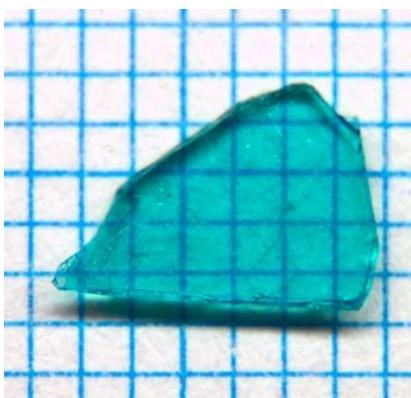
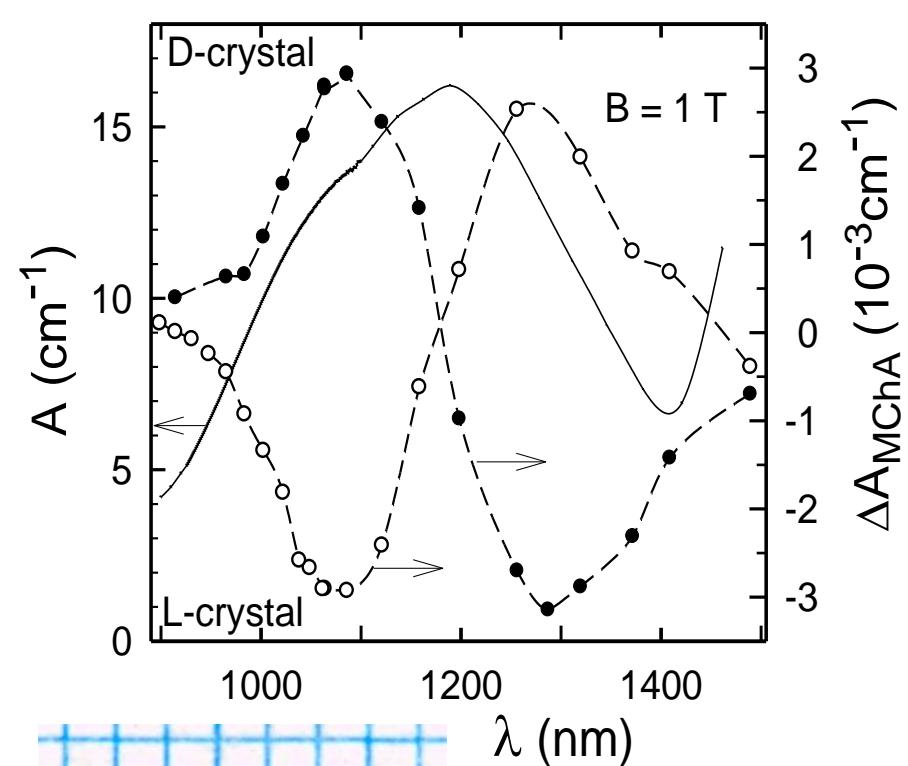
$$g \equiv \frac{I(\mathbf{B} \uparrow\uparrow \mathbf{k}) - I(\mathbf{B} \uparrow\downarrow \mathbf{k})}{I(\mathbf{B} \uparrow\uparrow \mathbf{k}) + I(\mathbf{B} \uparrow\downarrow \mathbf{k})}$$

Luminescence of $\text{Eu}(\text{D/L})\text{tfc}_3$



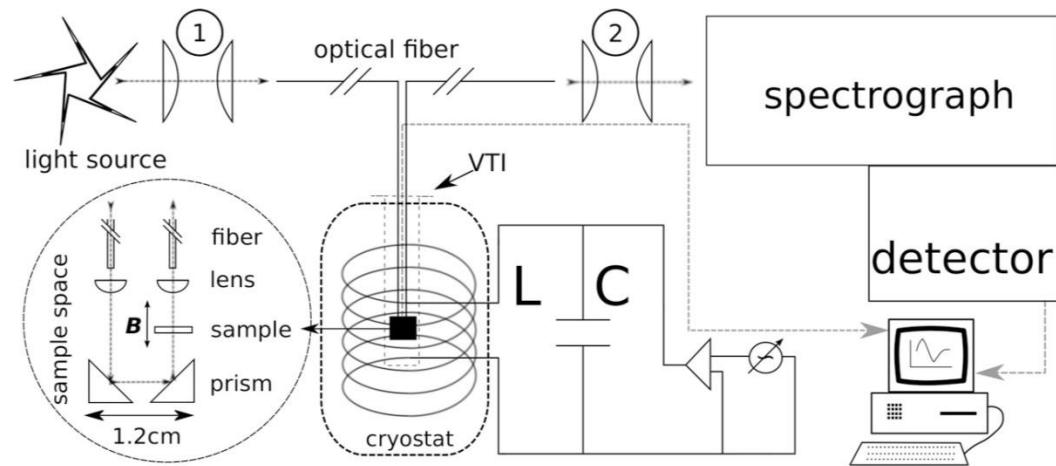
G.L.J.A. Rikken and E. Raupach, Nature 390, 493 (1997)

Magneto-chiral anisotropy in absorption

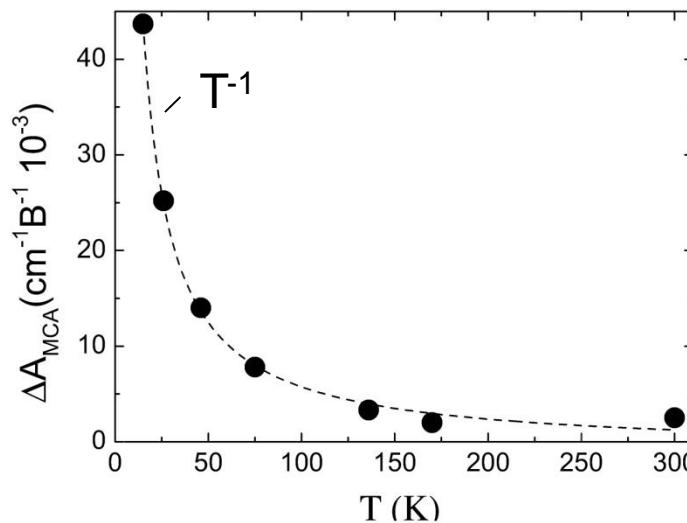
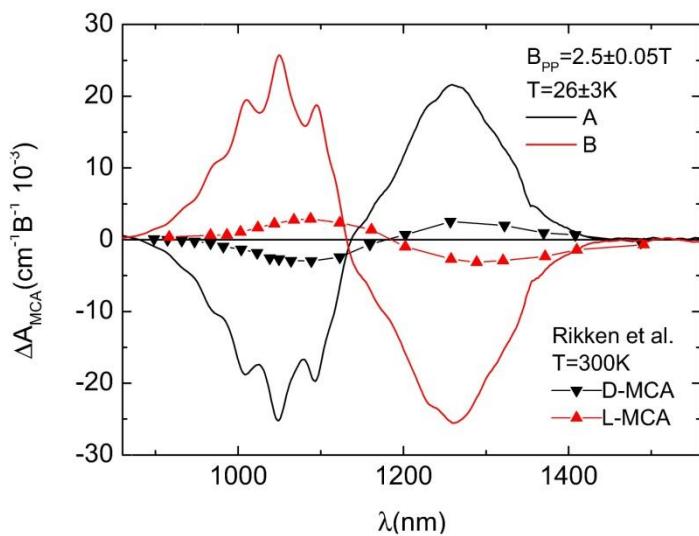


Cr(ox)_3 solution

Multichannel MChA spectrometer

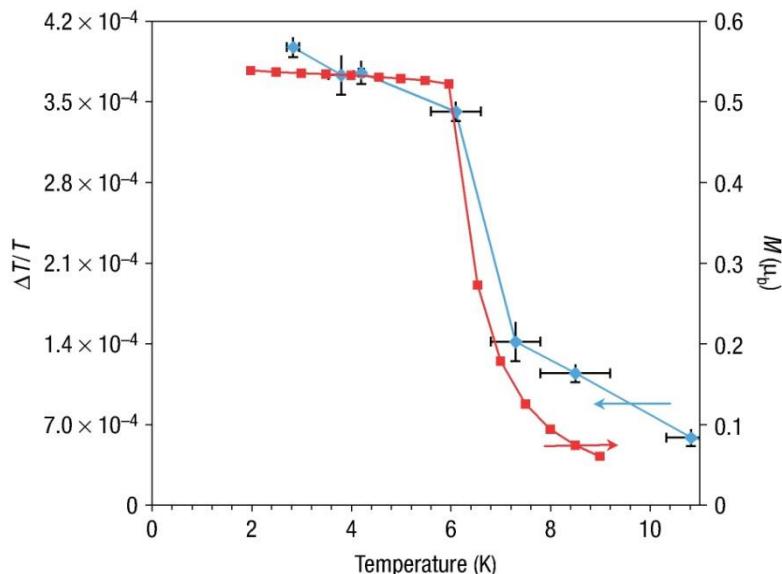
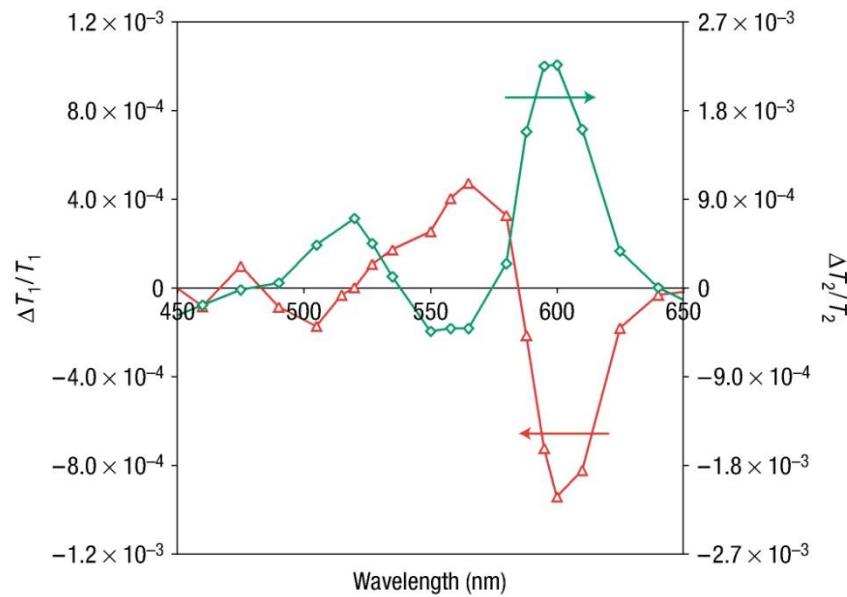
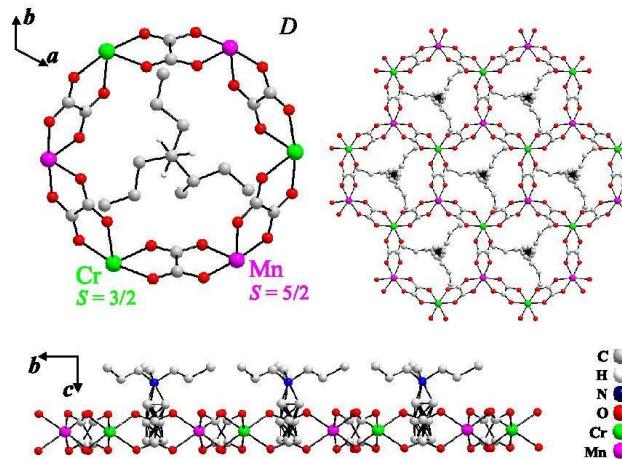


$\alpha - NiSO_4 \cdot 6H_2O$ paramagnetic

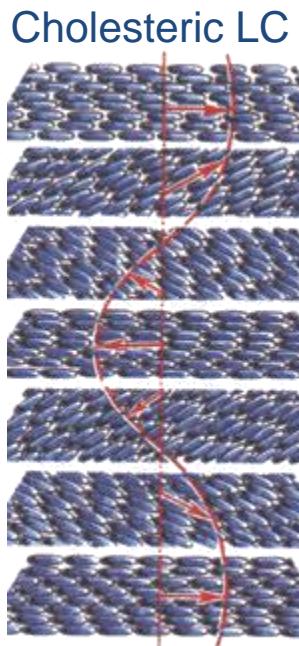


Kopnov and Rikken, Rev. Sci. Instr. 85, 053106 (2014)

MChA in the optical absorption of a chiral ferromagnet

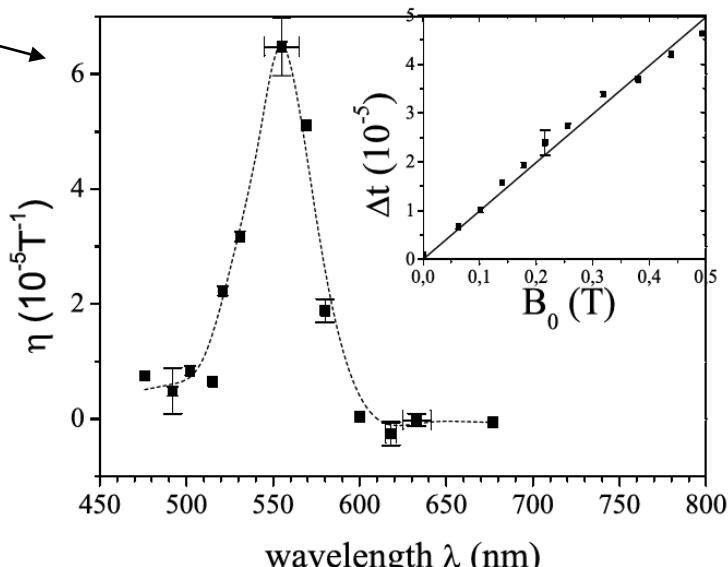
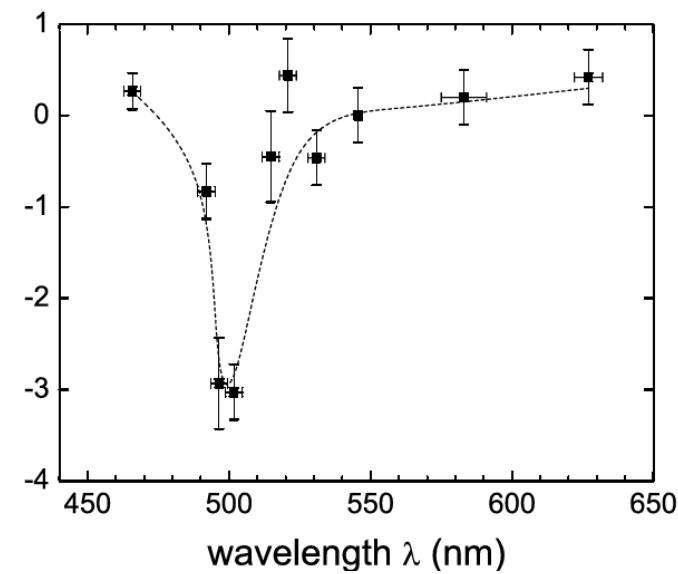
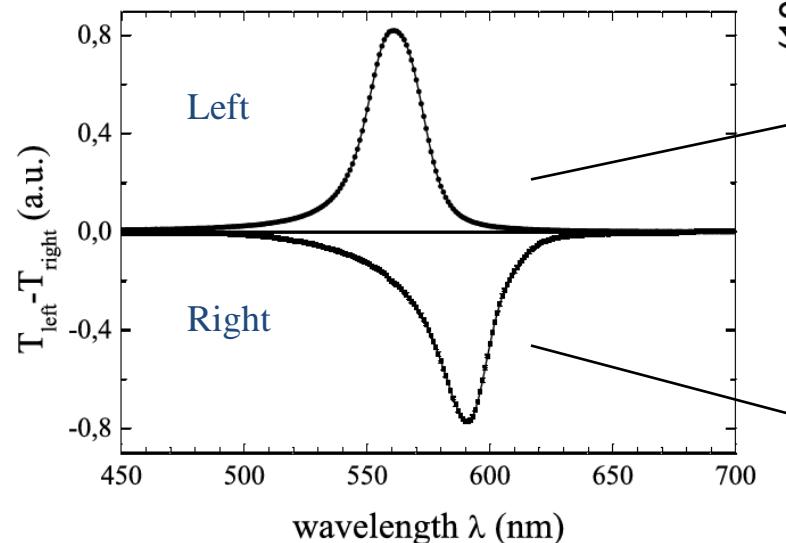


MChA in Bragg scattering



$$\eta \equiv \frac{T(\mathbf{B} \uparrow\uparrow \mathbf{k}) - T(\mathbf{B} \uparrow\downarrow \mathbf{k})}{T(\mathbf{B} \uparrow\uparrow \mathbf{k}) + T(\mathbf{B} \uparrow\downarrow \mathbf{k})}$$

(for unpolarized light)



$\Delta n_{molecule} \approx 10^{-10} T^{-1} \rightarrow$ Strong enhancement!



Other MChA manifestations in optics observed:

- Magneto-chiral birefringence, Kleindienst et al (1998), Vallet et al (2001)
- Magneto-chiral dichroism in X ray absorption (2002)
- Magneto-chiral dichroism in microwave absorption (2015)
- Magneto-chiral dichroism in THz absorption (2014)



ARTICLE

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Magnetochiral dichroism resonant with electromagnons in a helimagnet

S. Kibayashi^{1,*}, Y. Takahashi^{1,2,*}, S. Seki^{2,3} & Y. Tokura^{1,2}

VOLUME 88, NUMBER 23

PHYSICAL REVIEW LETTERS

10 JUNE 2002

X-Ray Magnetochiral Dichroism: A New Spectroscopic Probe of Parity Nonconserving Magnetic Solids

J. Goulon, A. Rogalev, F. Wilhelm, C. Goulon-Ginet, and P. Carra

PRL 114, 197202 (2015)

PHYSICAL REVIEW LETTERS

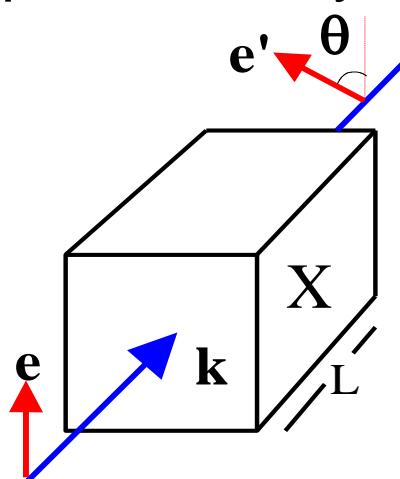
week ending
15 MAY 2015

Microwave Magnetochiral Dichroism in the Chiral-Lattice Magnet Cu₂OSeO₃

Y. Okamura,¹ F. Kagawa,² S. Seki,^{2,3} M. Kubota,^{2,4,*} M. Kawasaki,^{1,2} and Y. Tokura^{1,2}

MChA in photochemistry

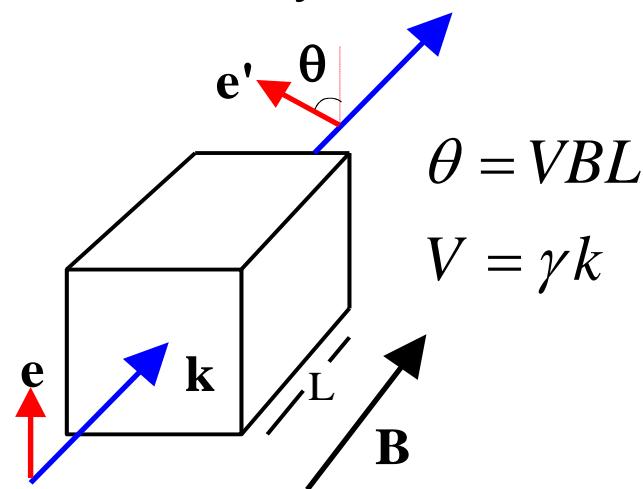
Optical activity



$$\theta = [\alpha^x] L$$

resembles the

Faraday effect:



$$\theta = VBL$$

$$V = \gamma k$$

Magnetically induced enantiomeric excess in a chemical reaction has been searched for since Pasteur, but is symmetry forbidden:

assume:

achiral starting product \xrightarrow{B} D product

parity operation:



achiral starting product \xrightarrow{B} L product

conflicting, so nonsense!

Magnetic fields in chiral photochemistry

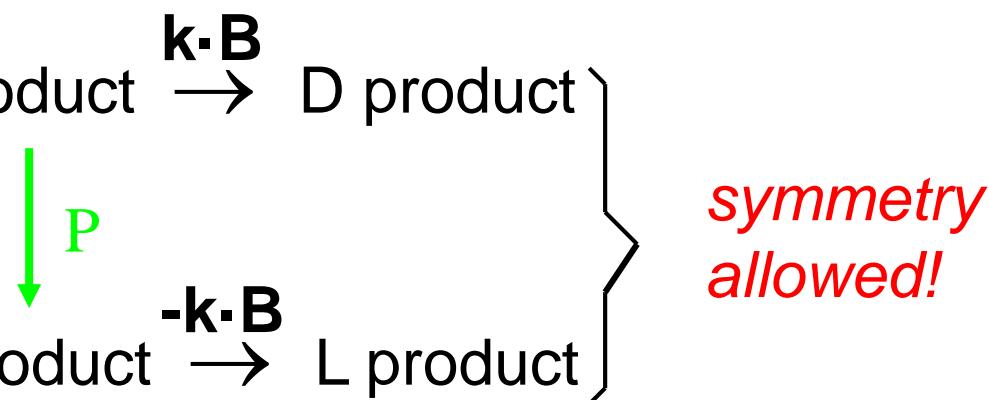
Magnetically induced enantiomeric excess in photochemistry is symmetry allowed:

photochemical reaction rate \propto absorption $\propto \mathbf{k} \cdot \mathbf{B}$

assume:



parity operation:

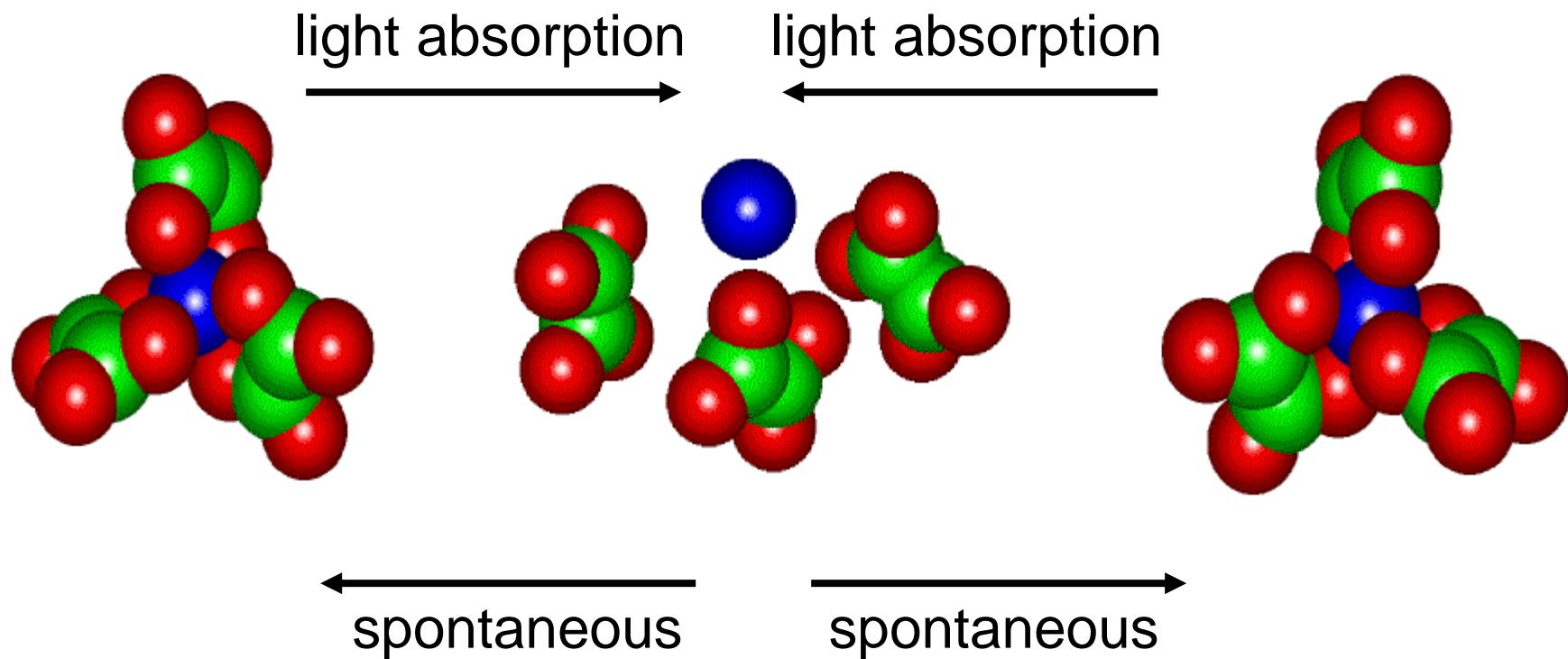


Magnetochiral anisotropy can drive a photochemical reaction into enantiomeric excess.

Explanation for the homochirality of Life?

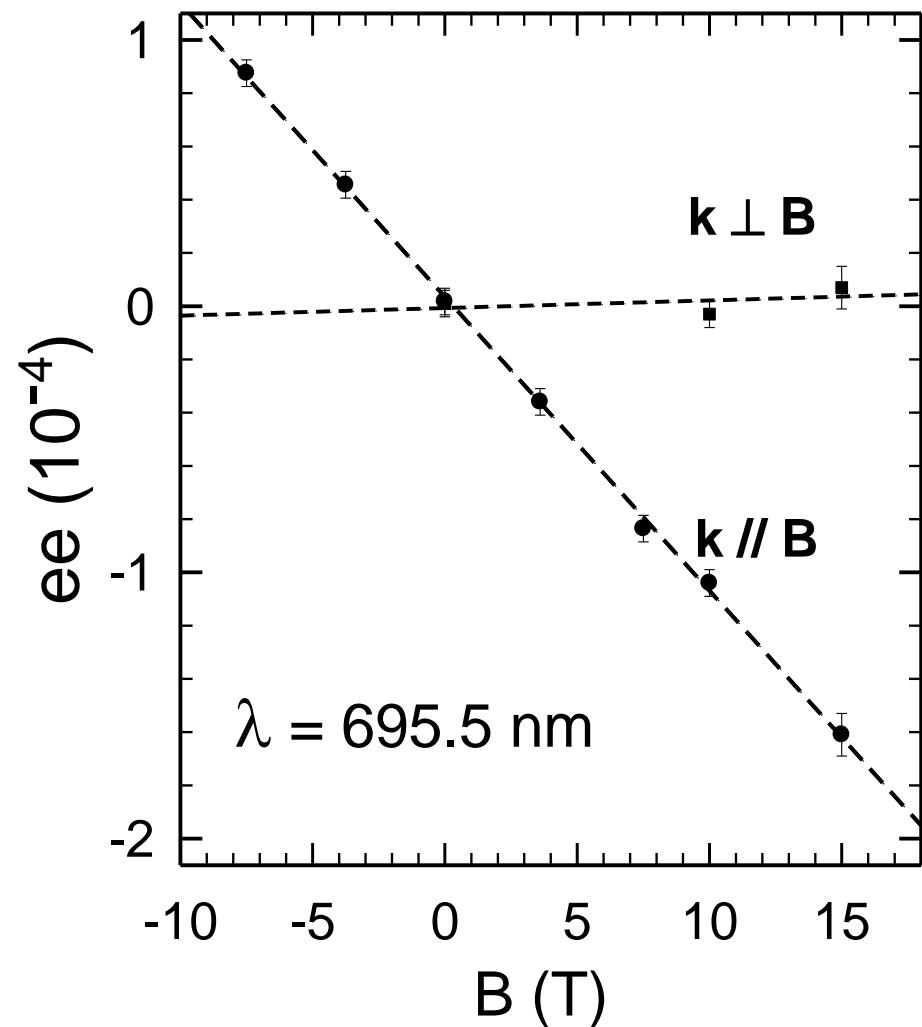
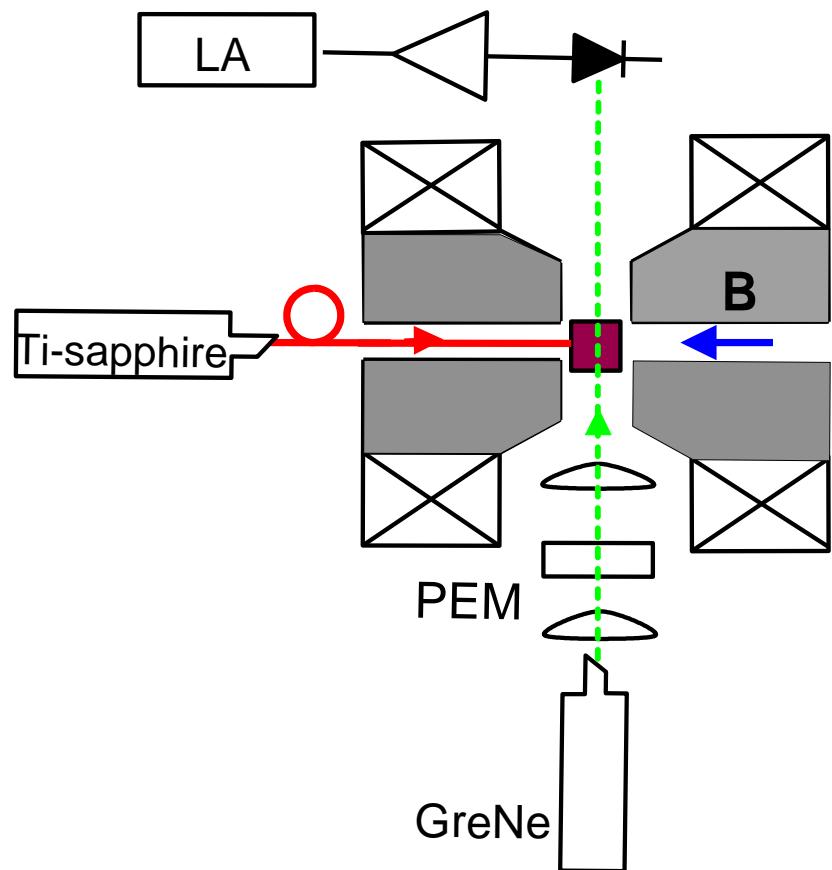
Magneto-chiral anisotropy in photochemistry

Photoresolution of Cr-oxalate:



In a parallel magnetic field, one enantiomer will absorb more unpolarized light and will therefore decompose more rapidly.

Enantioselective magneto-chiral photochemistry



G.L.J.A. Rikken and E. Raupach, Nature **405**, 932 (2000)



$$n^{\uparrow\uparrow} - n^{\uparrow\downarrow} \approx \frac{2\mu_0 c N B_z}{3\hbar} \left[\frac{(\omega_{jn}^2 + \omega^2)}{\hbar} (f^2 - g^2) A(G) - \frac{2\omega_{jn}\omega}{\hbar} (f^2 - g^2) A(A') \right. \\ \left. + \omega_{jn} f \left(B(G) + \frac{C(G)}{kT} \right) - \omega f \left(B(A') + \frac{C(A')}{kT} \right) \right],$$

(6.4.2a)

$$n'^{\uparrow\uparrow} - n'^{\uparrow\downarrow} \approx \frac{2\mu_0 c N B_z}{3\hbar} \left[\frac{2(\omega_{jn}^2 + \omega^2)}{\hbar} f g A(G) - \frac{4\omega_{jn}\omega}{\hbar} f g A(A') \right. \\ \left. + \omega_{jn} g \left(B(G) + \frac{C(G)}{kT} \right) - \omega g \left(B(A') + \frac{C(A')}{kT} \right) \right],$$

$$A(G) = \varepsilon_{\alpha\beta\gamma} \frac{1}{d_n} \sum_n (m_{j\gamma} - m_{n\gamma}) \text{Re} (\langle n | \mu_\alpha | j \rangle \langle j | m_\beta | n \rangle), \quad (6.4.2c)$$

$$B(G) = \varepsilon_{\alpha\beta\gamma} \frac{1}{d_n} \sum_n \text{Re} \left[\sum_{k \neq n} \frac{\langle k | m_\gamma | n \rangle}{\hbar\omega_{kn}} (\langle n | \mu_\alpha | j \rangle \langle j | m_\beta | k \rangle + \langle n | m_\beta | j \rangle \langle j | \mu_\alpha | k \rangle) \right. \\ \left. + \sum_{k \neq j} \frac{\langle j | m_\gamma | k \rangle}{\hbar\omega_{kj}} (\langle n | \mu_\alpha | j \rangle \langle k | m_\beta | n \rangle + \langle n | m_\beta | j \rangle \langle k | \mu_\alpha | n \rangle) \right], \quad (6.4.2d)$$

$$C(G) = \varepsilon_{\alpha\beta\gamma} \frac{1}{d_n} \sum_n m_{n\gamma} \text{Re} (\langle n | \mu_\alpha | j \rangle \langle j | m_\beta | n \rangle); \quad (6.4.2e)$$

$$A(A') = \frac{\omega}{15d_n} \sum_n (m_{j\beta} - m_{n\beta}) \text{Im} (3 \langle n | \mu_\alpha | j \rangle \langle j | \Theta_{\alpha\beta} | n \rangle - \langle n | \mu_\beta | j \rangle \langle j | \Theta_{\alpha\alpha} | n \rangle), \quad (6.4.2f)$$

$$B(A') = \frac{\omega}{15d_n} \sum_n \text{Im} \left\{ \sum_{k \neq n} \frac{\langle k | m_\beta | n \rangle}{\hbar\omega_{kn}} [3(\langle n | \mu_\alpha | j \rangle \langle j | \Theta_{\alpha\beta} | k \rangle - \langle n | \Theta_{\alpha\beta} | j \rangle \langle j | \mu_\alpha | k \rangle) \right. \\ \left. - (\langle n | \mu_\beta | j \rangle \langle j | \Theta_{\alpha\alpha} | k \rangle - \langle n | \Theta_{\alpha\alpha} | j \rangle \langle j | \mu_\beta | k \rangle)] \right. \\ \left. + \sum_{k \neq j} \frac{\langle j | m_\beta | k \rangle}{\hbar\omega_{kj}} [3(\langle n | \mu_\alpha | j \rangle \langle k | \Theta_{\alpha\beta} | n \rangle - \langle n | \Theta_{\alpha\beta} | j \rangle \langle k | \mu_\alpha | n \rangle) \right. \\ \left. - (\langle n | \mu_\beta | j \rangle \langle k | \Theta_{\alpha\alpha} | n \rangle - \langle n | \Theta_{\alpha\alpha} | j \rangle \langle k | \mu_\beta | n \rangle)] \right\}, \quad (6.4.2g)$$

$$C(A') = \frac{\omega}{15d_n} \sum_n m_{n\beta} \text{Im} (3 \langle n | \mu_\alpha | j \rangle \langle j | \Theta_{\alpha\beta} | n \rangle - \langle n | \mu_\beta | j \rangle \langle j | \Theta_{\alpha\alpha} | n \rangle). \quad (6.4.2h)$$

MChA microscopic theory

Barron & Vbranchich 1984:

Harmonic oscillator theory MChA (Donaire, Rikken, Van Tigelen 2013)

Optical rotation β_{OR}

$$\text{MChA} \quad \Delta n_{MChA} = \frac{23}{10} \frac{\omega^2}{q\varepsilon_0 c} \alpha_E \beta_{OR}^{D/L} B_0$$

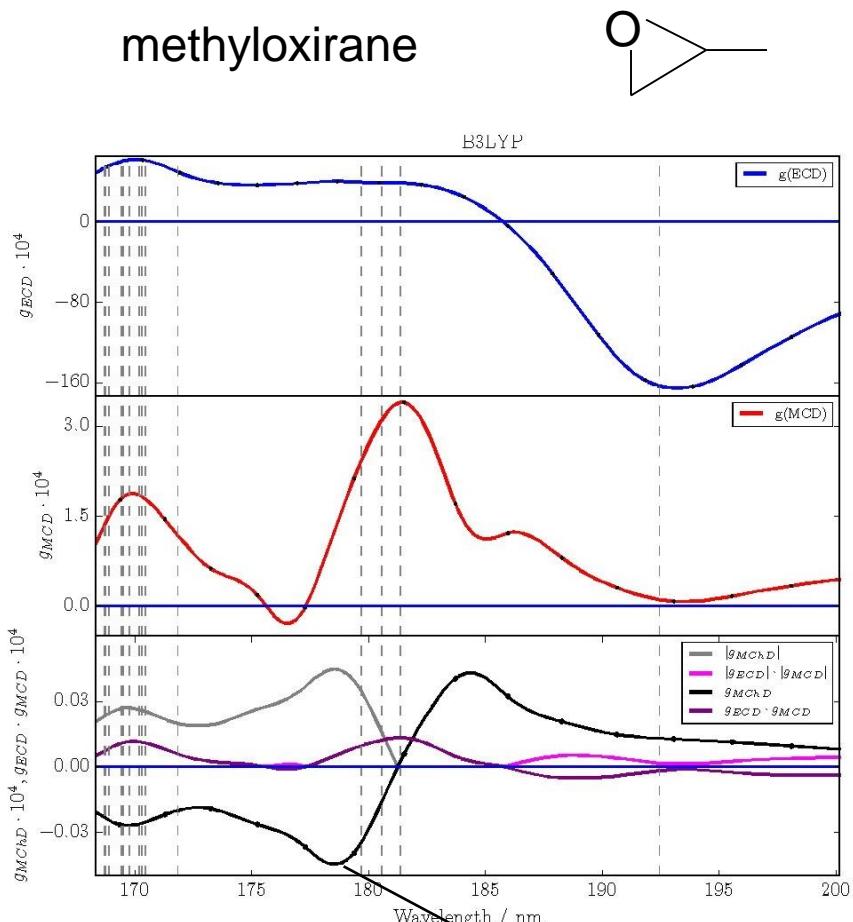
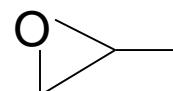
Molecule	HO theory	Experiment
limonene	2.6	3.2
tartaric acid	0.12	0.90
proline	0.4	2.7

Units 10^{-10} T^{-1}



Density functional theory MChA (Coriani, Rizzo, Rikken 2016)

methyloxirane



$$\Delta\epsilon / \epsilon = 5 \cdot 10^{-6} T^{-1}$$

Experimental challenge!



MChA “wave” effects still to be observed:

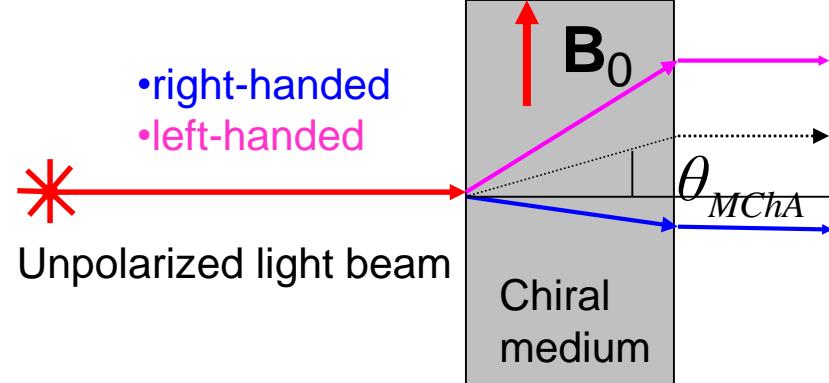
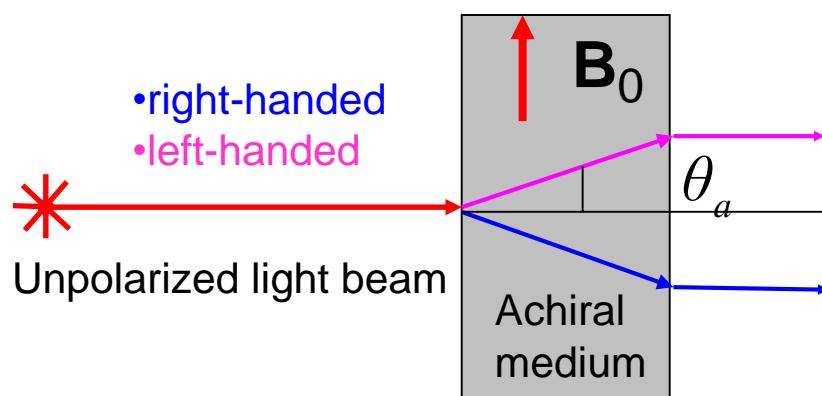
- Magneto-chiral deflection of light
- Magneto-chiral anisotropy in light diffusion
- Magneto-chiral anisotropy in ultra-sound propagation
- Magneto-chiral enantio-selectivity in NMR/EPR
- Magneto-chiral anisotropy in magnon/helicon/plasmon propagation

Magneto-chiral deflection of light

$$\varepsilon(\omega, \mathbf{k}, \mathbf{B}_0)_{\pm}^{D/L} = \varepsilon(\omega) \pm \alpha(\omega)^{D/L} k \pm \gamma(\omega) B_0 + \Omega(\omega)^{D/L} \mathbf{k} \cdot \mathbf{B}_0$$

Poynting vector: $\mathbf{S} = \frac{c}{8\pi} \operatorname{Re}(\mathbf{E}^* \times \mathbf{B}) - \frac{\omega}{16\pi} \frac{\partial \varepsilon_{ik}}{\partial \mathbf{k}} E_i E_k$

Two cases:



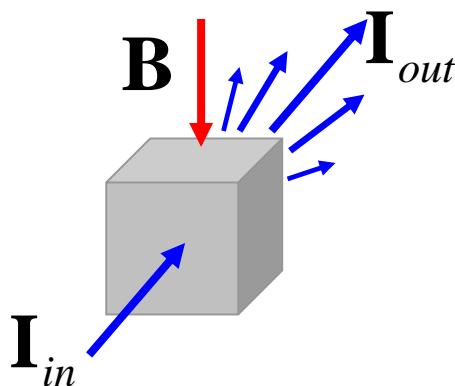
deflection: $\theta_a = \frac{\pi \gamma B_0}{\lambda}$

Observed: Rikken et al 1996

deflection: $\theta_{MChA} = \frac{\pi \Omega B_0}{\lambda}$

Never observed

MChA in light diffusion



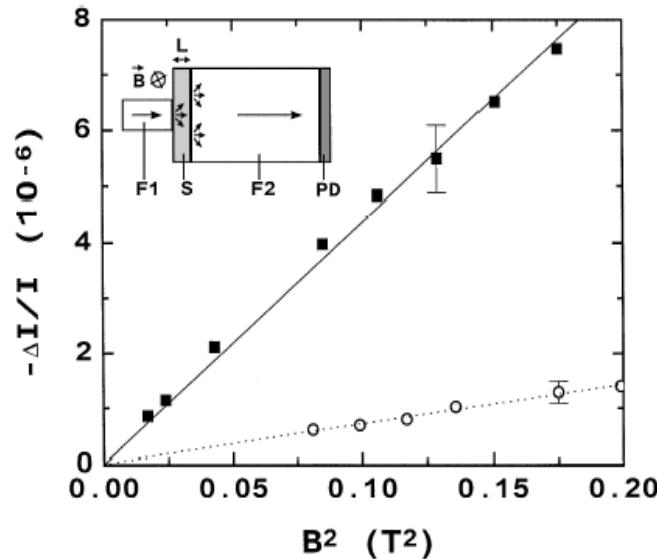
Chiral medium:

$$\frac{I_{out}}{I_{in}} = T_0 + f(\Omega k Bl^*) + g(VBl^*)^2$$

Never observed

Achiral medium:

$$\frac{I_{out}}{I_{in}} = T_0 + g(VBl^*)^2$$

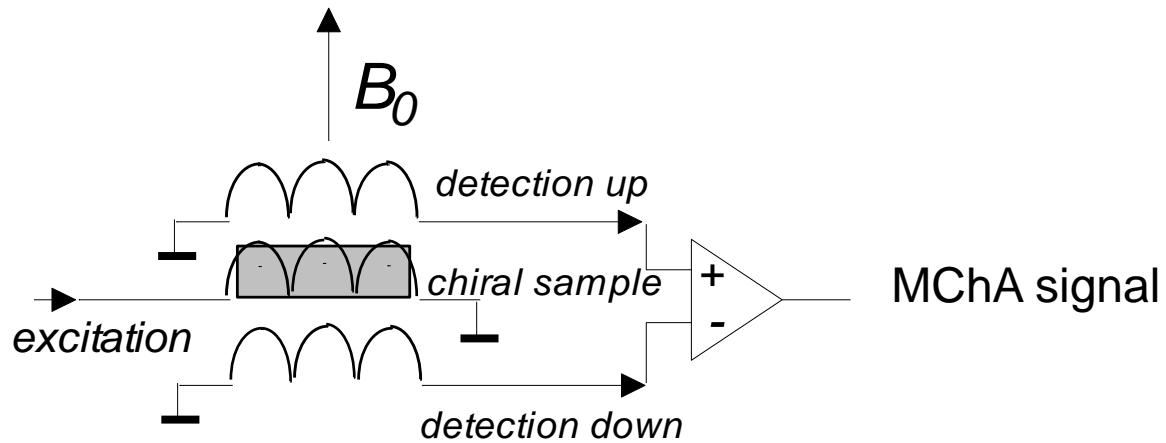


A. Sparenberg, et al PRL 79, 757 (1997)

Magneto-chiral enantio-selectivity in NMR/EPR

NMR/EPR is based on magnetic circular dichroism of a spin system and NMR/EPR in a chiral spin system should show magneto-chiral anisotropy, in absorption and in emission, and therefore enantio-selectivity.

Possible MChA spin echo experiment





MChA in non-linear optics

- Inverse magneto-chiral anisotropy
- Magnetic field induced second harmonic generation



Inverse optical magneto-chiral anisotropy

Inverse Faraday effect: magnetization induced by circularly polarized light in all media

$$\vec{M}_{IFE}^{\pm} \propto V \vec{E}^{\omega} \times \vec{E}^{\omega*} \propto V I_{\pm}^{\omega} k \quad (\text{Van der Ziel, 1965})$$

Inverse magneto-chiral anisotropy: magnetization induced by unpolarized light in chiral media

$$\vec{M}_{IMChA}^{D/L} \propto \Omega^{D/L} \vec{k} \left(\vec{E}^{\omega} \cdot \vec{E}^{\omega} \right) \propto \Omega^{D/L} I^{\omega} k$$

Not observed
(difficult to suppress IFE)

Magnetic field induced second harmonic generation

Electric field induced second harmonic generation (EFISHG):

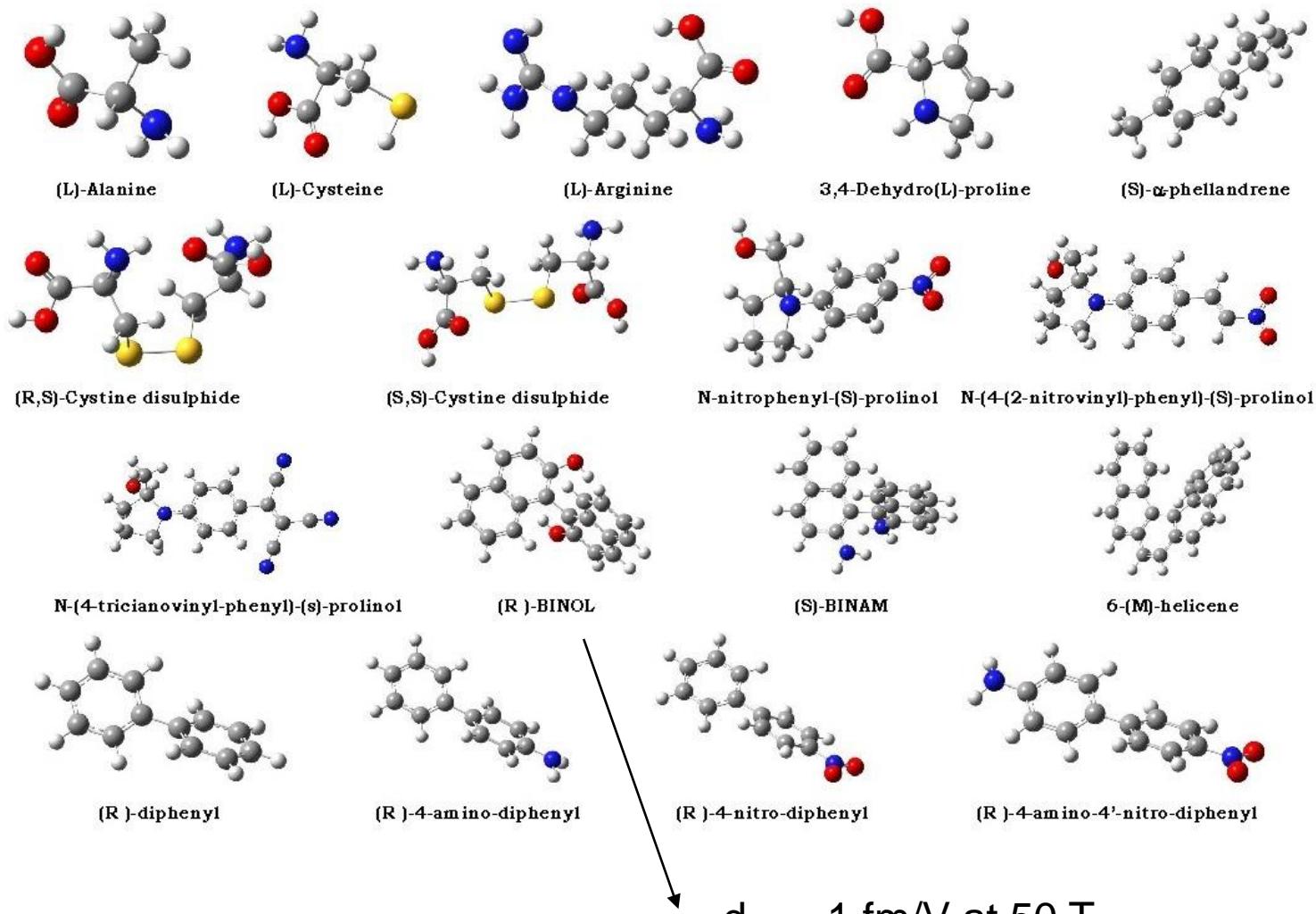
$$\vec{P}^{2\omega} = \chi \vec{E}^\omega \vec{E}^\omega \vec{E}_0 \rightarrow I^{2\omega} \propto E_0^2 (I^\omega)^2 \quad \text{in all media}$$

Magnetic field induced second harmonic generation (MFISHG):

$$\vec{P}^{2\omega} = \chi_M^{D/L} \left(\frac{\partial \vec{E}^\omega}{\partial t} \cdot \vec{B}_0 \right) \vec{E}^\omega \rightarrow I^{2\omega} \propto (\omega \chi_M^{D/L} B_0)^2 (I^\omega)^2 \quad \text{Only In chiral media}$$

Never observed

Ab initio DFT calculations MFISHG (Rizzo, Rikken, Mathevet 2016)



$$d_{33} = 1 \text{ fm/V at } 50 \text{ T}$$

Experimental challenge!



Simple picture MFISHG

$$\frac{\partial \vec{E}^\omega}{\partial t} = \chi \frac{\partial \vec{P}^\omega}{\partial t} = \chi \vec{J}^\omega \quad \text{so}$$

$$\vec{P}_M^{2\omega} = \chi_M^{D/L} \left(\frac{\partial \vec{E}^\omega}{\partial t} \cdot \vec{B}_0 \right) \vec{E}^\omega = \chi \cdot \chi_M^{D/L} \left(\vec{J}^\omega \cdot \vec{B}_0 \right) \vec{E}^\omega$$

↓

MFISHG is electrical MChA at optical frequencies!



Magneto-chiral anisotropy in electrical transport

Conjecture: magneto-chiral anisotropy exists in all momentum transport through chiral media, both *ballistic* and *diffusive*.

Possible manifestations:

Thermal conductivity, molecular diffusion,.....

Electrical resistance: $R(\mathbf{B}, \mathbf{I})^{D/L} = R_0(1 + \beta B^2 + \Omega^{D/L} \mathbf{B} \cdot \mathbf{I})$

$$\frac{R(\mathbf{B}, \mathbf{I})^{D/L} - R(-\mathbf{B}, \mathbf{I})^{D/L}}{R_0} = 2\Omega^{D/L} \mathbf{B} \cdot \mathbf{I} \quad \text{linear MR!}$$

Onsager's relation and magneto-chiral anisotropy

Generalized diffusive transport: $S_i = \sigma_{ij} F_j$

Onsager's relation: $\sigma_{ij} = \sigma_{ji}^*$ (* = time reversal)

In a magnetic field:

$$\sigma_{ij}(\mathbf{B}) = \sigma_{ji}(-\mathbf{B}) \Rightarrow \sigma_{ii}(\mathbf{B}) = \sigma_{ii} \left(1 + \beta B^2 + \dots \right)$$

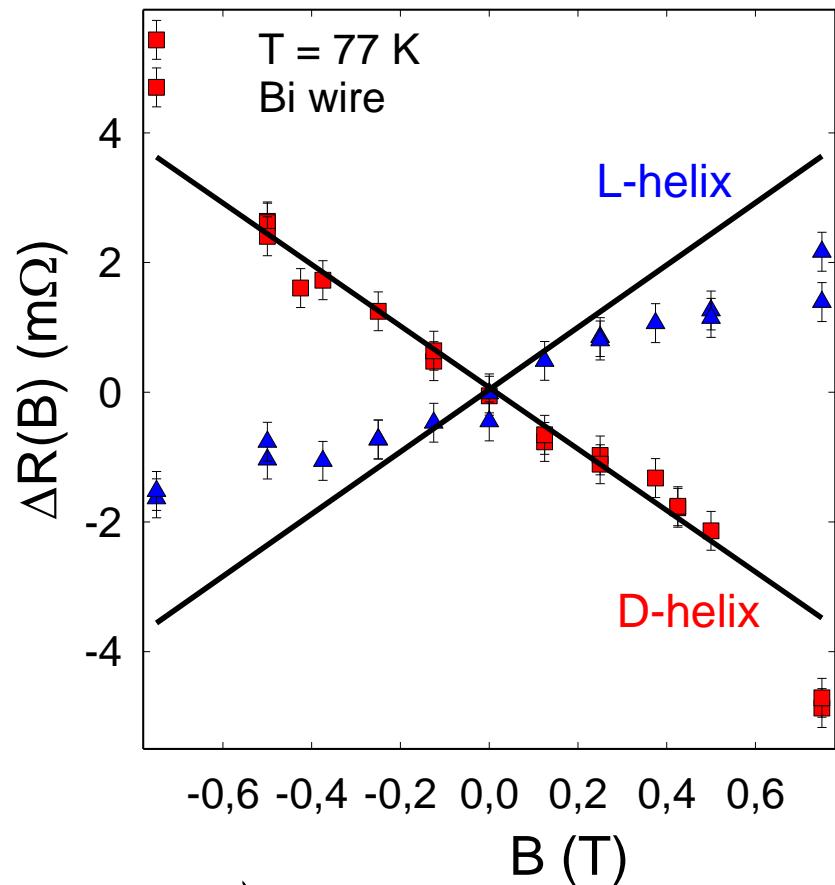
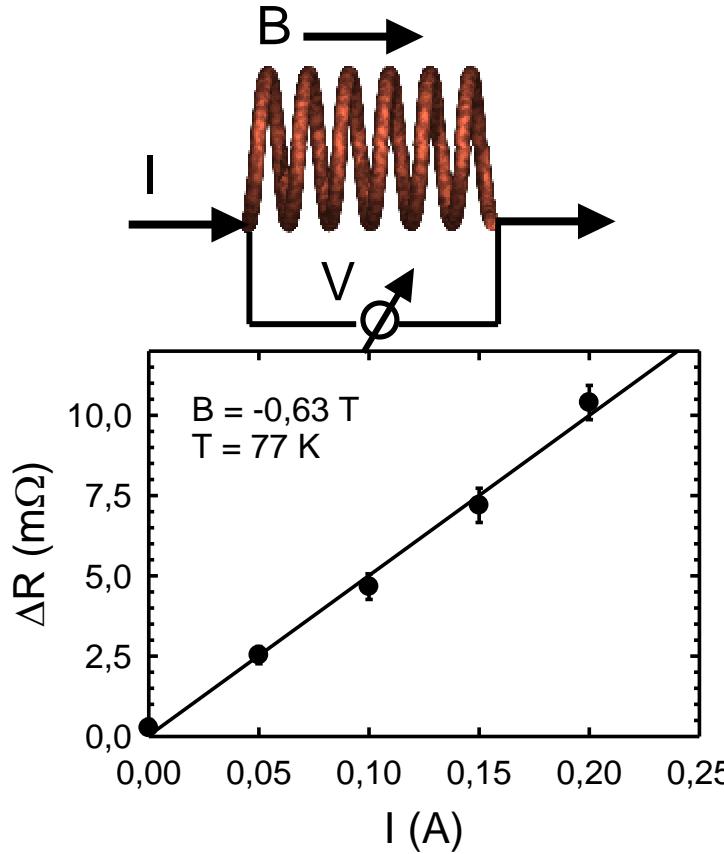
In a chiral medium in a magnetic field:

$$\sigma_{ij}^{D/L}(\mathbf{k}, \mathbf{B}) = \sigma_{ji}^{D/L}(-\mathbf{k}, -\mathbf{B}) \Rightarrow$$

$$\sigma_{ii}^{D/L}(\mathbf{k}, \mathbf{B}) = \sigma_{ii} \left(1 + \Omega^{D/L} \mathbf{B} \cdot \mathbf{k} + \beta B^2 + \dots \right)$$

So there is no symmetry argument against MChA in the two terminal resistance of a chiral conductor.

Observation of MChA in electrical resistance I; self field

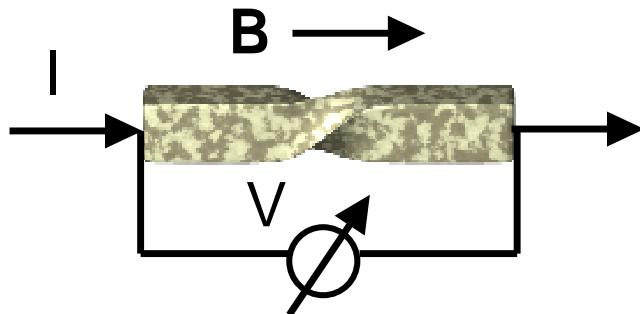


« Theory »:

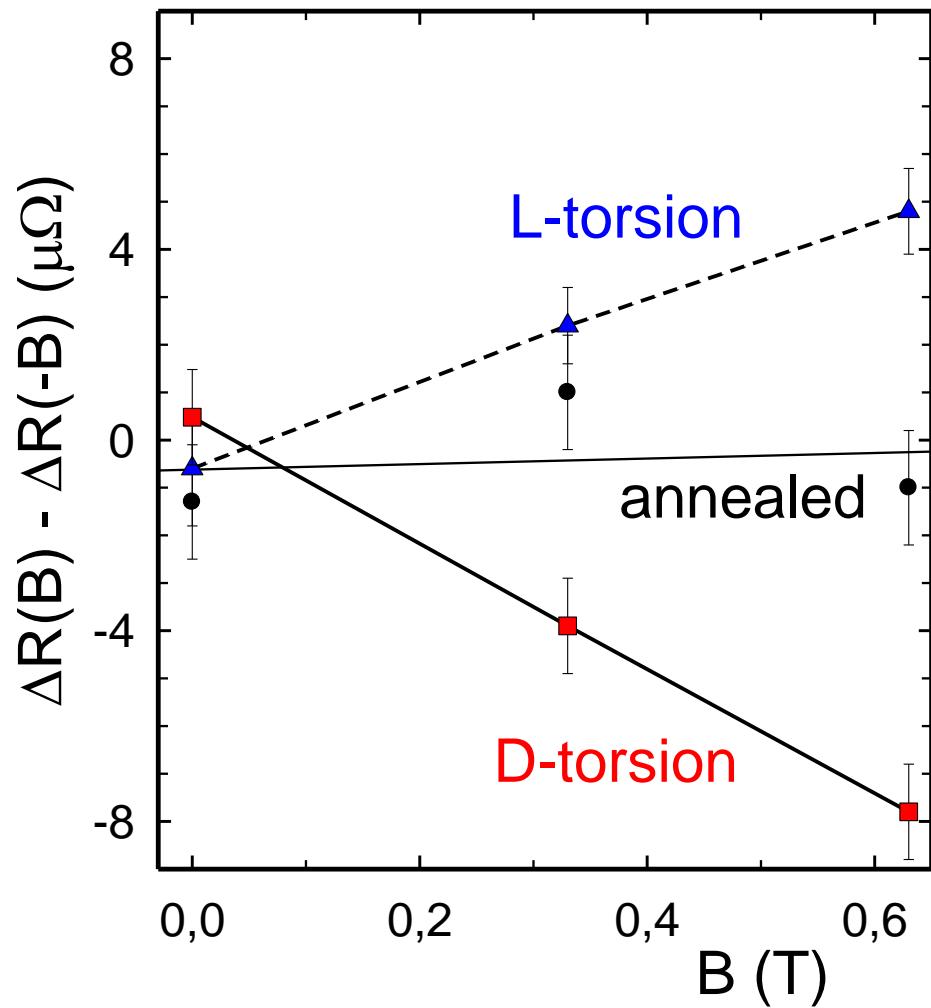
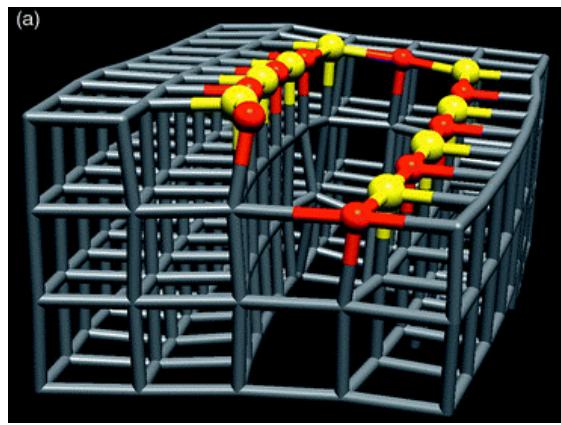
$$\begin{aligned}
 R(\mathbf{B}_{ext}, \mathbf{I})^{D/L} &= R_0 \left(1 + \beta \left(\mathbf{B}_{ext} + \mathbf{B}_{sf} (\mathbf{I}) \right)^2 \right) = \\
 &= R_0 \left(1 + \beta \left(B_{ext} + \alpha^{D/L} I \right)^2 \right) = R_0 \left(1 + \beta B_{ext}^2 + 2\alpha^{D/L} \beta B_{ext} I + .. \right)
 \end{aligned}$$

eMChA!

Observation of MChA in electrical resistance II; scattering

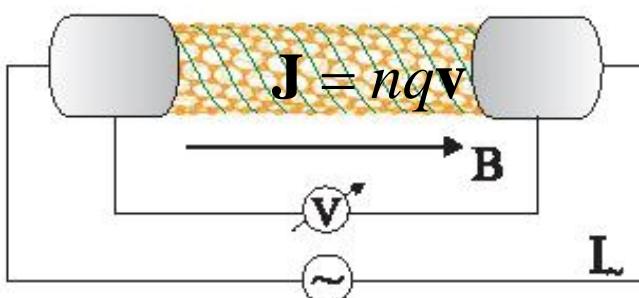
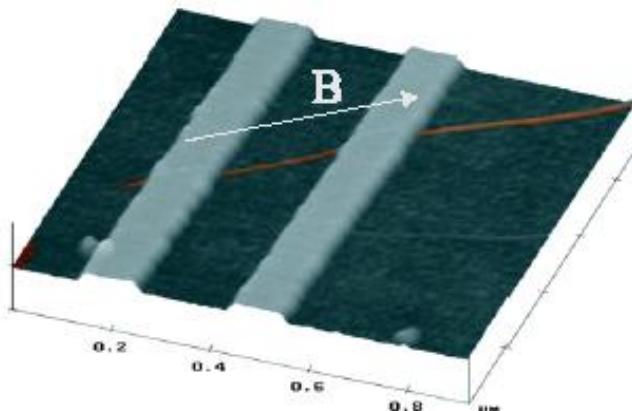


Explanation: scattering by screw dislocations

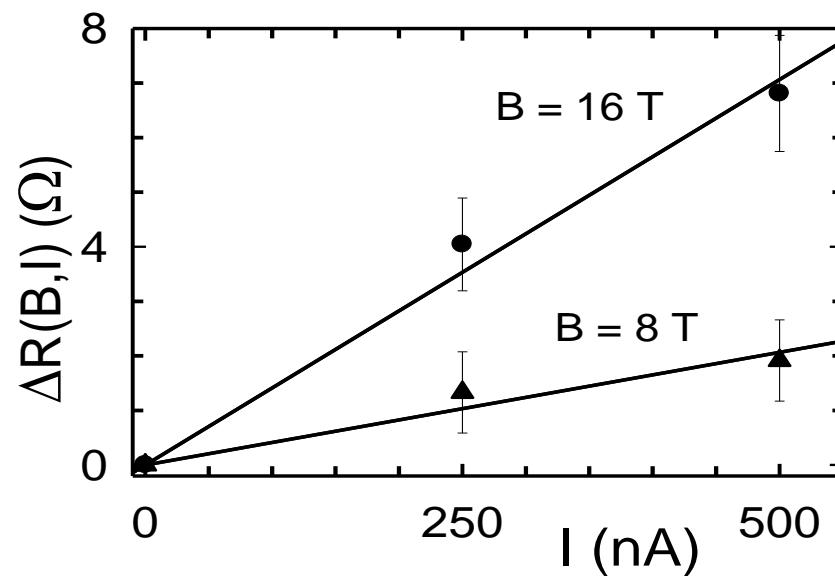
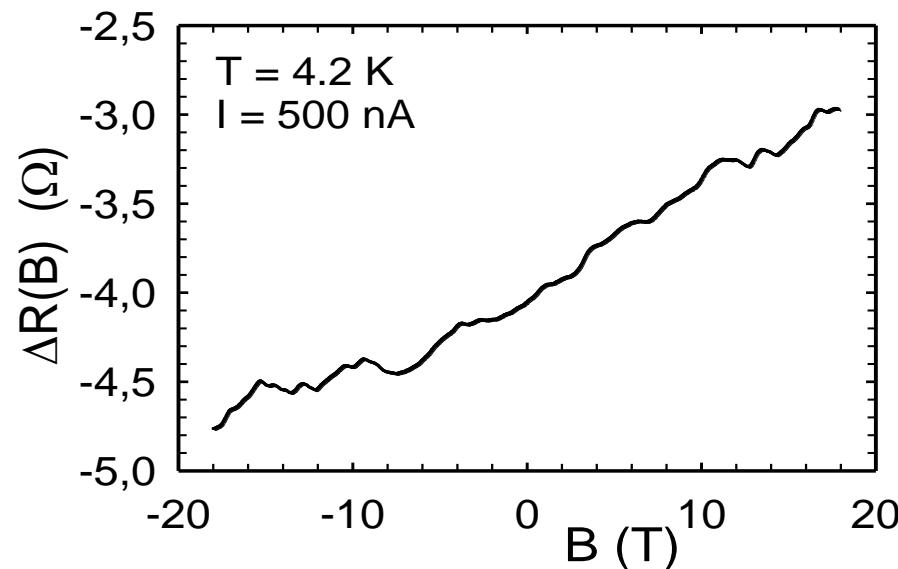


Observation of MChA in electrical resistance III

Carbon nanotube

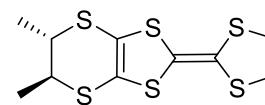


V. Krstic et al, J. Chem. Phys. 117,
11315 (2002)

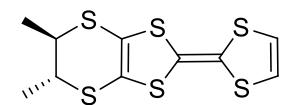


Observation of MChA in electrical resistance IV; bulk

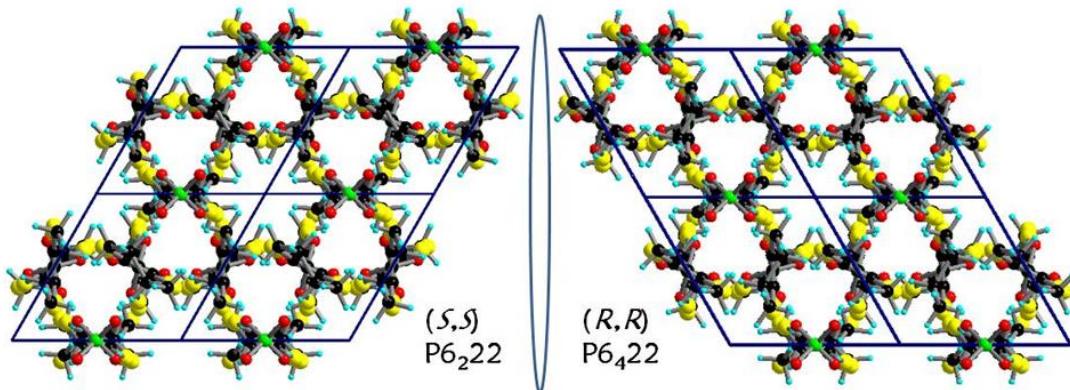
- Of the 230 possible crystal space groups, 65 are chiral
- So there should be plenty of bulk chiral metals
- However, apart from Xray crystallography, no sign of chirality in 3D metals has been observed
- Difficult to obtain a chiral metal of given handedness
- Solution: organic 3D metal, built from chiral molecules



(*S,S*)-DM-EDT-TTF

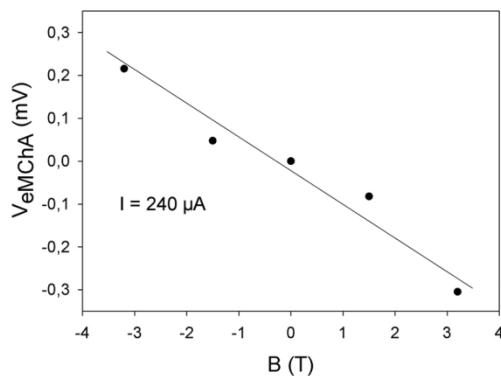


(*R,R*)-DM-EDT-TTF

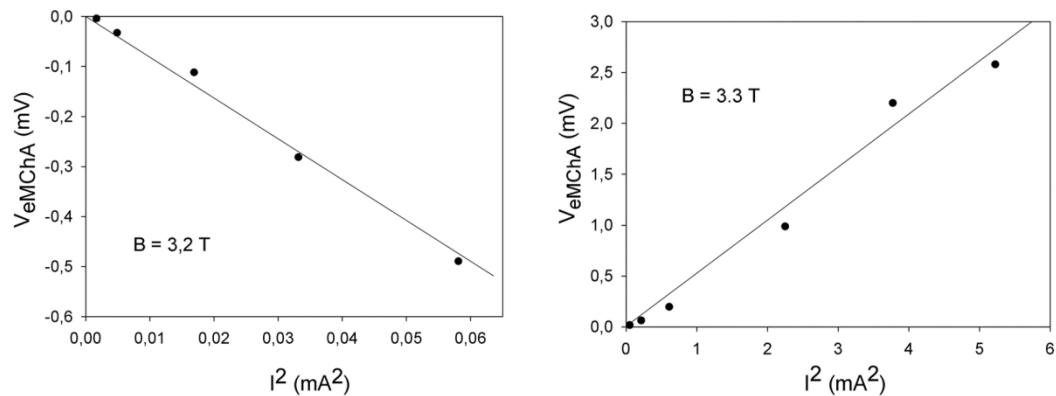


Result eMChA in bulk metal

SS



RR



Comparison eMChA

	Bi	SWCNT	$[\text{DM-EDT-TTF}]_2\text{ClO}_4$
β (T^{-2})	10^2	10^{-4}	$< 10^{-3}$
γ ($T^{-1} \text{ A}^{-1}$)	10^{-3}	10^3	10^{-2}
γ ($m^2 T^{-1} \text{ A}^{-1}$)	10^{-8}	10^{-14}	10^{-10}

F. Pop, G. Rikken et al, Nature Comm. 2014

The effect exists in 3D, microscopic explanation?



Other MChA transport effects still to be observed:

-MChA in thermal conductivity

-Magneto-chiral induction: $\vec{E} = \chi^{D/L} \frac{\partial \vec{B}}{\partial t}$

-Inverse electrical magneto-chiral anisotropy: $\vec{M} = \chi^{D/L} \vec{I}$

Magneto-mechanical effects

Quadratic effects:

Magnetic alignment $\propto \vec{M} \cdot \vec{B}$

Magnetic force $\propto \nabla \vec{M} \cdot \vec{B}$

Magneto-striction $\propto B^2$

Magnetic torque $\propto \vec{M} \times \vec{B}$

Linear effects:

Einstein-deHaas effect (1915): $\vec{L} \propto \vec{M}$ (Gyromagnetic effects)

Barnett effect (IEdHe, 1915): $\vec{M} \propto \vec{L}$

Wiedemann effect (1858): chiral distortion $\propto \vec{I} \cdot \vec{B}$

Matteucci effect (IWe): $I \sim$ chiral distortion in B (Magneto-chiral effects)

Anything else?

Additionnal symmetry allowed magneto-mechanical effects

Magneto-electric:

$$\vec{M} = \zeta' \vec{E} \times \vec{p} \quad (\text{Rontgen, 1888})$$

$$\vec{P} = \zeta'' \vec{B} \times \vec{p} \quad (\text{Wilson, 1905}) \quad \text{Relativistic effects}$$

$$\vec{p} = \zeta \vec{E} \times \vec{B} \quad ??$$

Magneto-chiral:

$$\vec{p} = \zeta^{D/L} \vec{B} \quad \text{with} \quad \zeta^D = -\zeta^L \quad (\text{« magneto-chiro-dynamical effect », unobserved!})$$

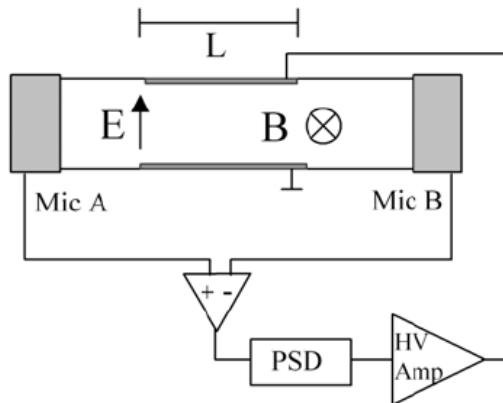
$$\vec{M} = \zeta'^{D/L} \vec{p} \quad (\text{« inverse magneto-chiro-dynamical effect », unobserved!})$$

Mechanical magneto-electric anisotropy

Symmetry allowed: $\vec{p} = \zeta \vec{E} \times \vec{B}$

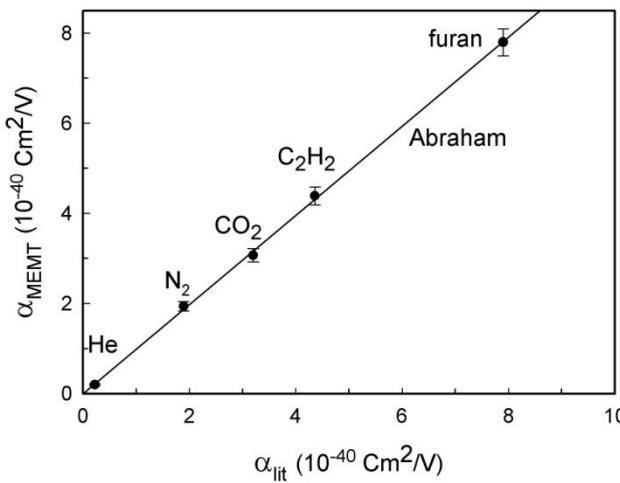
Dimension ζ must be $C^2 s^2 kg^{-1}$ which is the dimension of electric polarizability α

Experiment on gases:



Sound pressure

$$P_{acoustic} \propto \frac{dp}{dt} = \zeta \frac{dE}{dt} \times B$$



Mechanical magneto-electric anisotropy exists!

**It is called the Abraham force in electrodynamics
and is a result of the Lorentz & Coulomb forces**

$$\zeta = \alpha$$

Rikken et al, PRL 107, 170401 (2011)

The magneto-chirodynamical effect

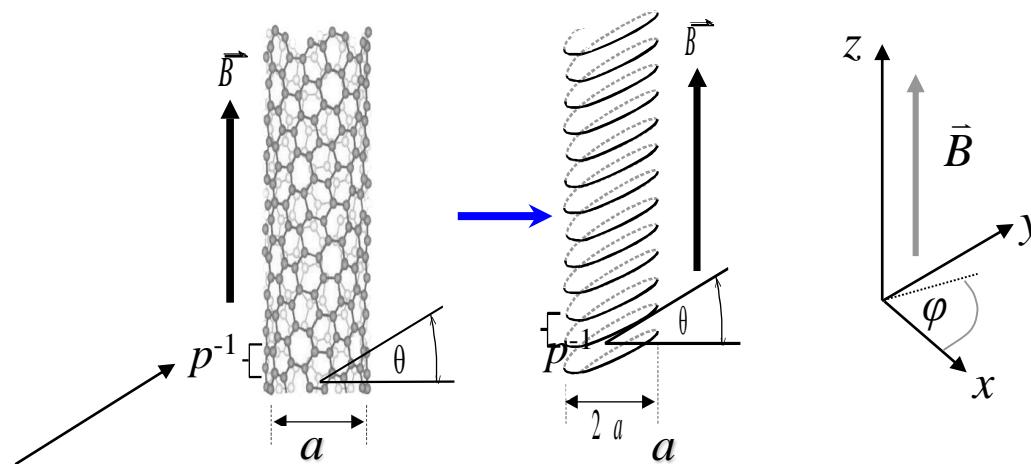
$$\vec{p} = \zeta^{D/L} \vec{B}$$

Part 1

-The effect is symmetry allowed but has no classical explanation

-Hypothesis: It results from coupling between linear and angular momentum intrinsic in chiral wavefunctions

-Model: Free electron on a helix



pitch: $p = (2\pi|b|)^{-1}$

Hamiltonian:

$$\hat{H} = -\frac{\hbar^2}{2m(a^2 + b^2)} \frac{\partial^2}{\partial\varphi^2} - i\hbar \frac{q}{2m} \frac{a^2}{a^2 + b^2} B_{ext} \frac{\partial}{\partial\varphi} + \frac{q^2 a^2}{8m} B_{ext}^2$$



normalized eigenstates with periodic boundary conditions:

$$\Psi_n(\varphi) = \sqrt{2\pi N|b|}^{-1} \exp(in\varphi/N)$$

$n = \dots, -1, 0, 1, 2, \dots$
N number of turns

linear momentum:

$$\langle p_{z,n} \rangle = -\frac{n\hbar}{N(a^2 + b^2)} \frac{b}{|b|}$$

orbital magnetic moment

$$\langle m_{z,n} \rangle = \frac{en\hbar}{2m_e N(a^2 + b^2)} \frac{a^2}{|b|}$$

so

$$p = -\frac{2m_e b}{ea^2} m = -\frac{2m_e b \chi}{ea^2} B$$

For a perfect typical CNT: $v/B = 10^{-4} \text{ m/s/T}$

(Krstic, Wagniere and Rikken 2004)



The magneto-chirodynamical effect

$$\vec{p} = \zeta^{D/L} \vec{B} \quad \text{Part 2}$$

-The effect is symmetry allowed but has no classical explanation

-Hypothesis:

It results from “optical” MChA interacting with the quantum vacuum fluctuations

Model Hamiltonian of harmonic oscillator + QV: $H = H_0 + H_{EM} + W$ with

$$H_0 = \sum_{i=e,N} \frac{1}{2m_i} [\mathbf{p}_i - q_i \mathbf{A}_0(\mathbf{r}_i)]^2 + V^{HO} + V_C, \quad (1)$$

$$H_{EM} = \sum_{\mathbf{k}, \epsilon} \hbar \omega_{\mathbf{k}} (a_{\mathbf{k}\epsilon}^\dagger a_{\mathbf{k}\epsilon} + \frac{1}{2}) + \frac{1}{2\mu_0} \int d^3r \mathbf{B}_0^2, \quad (2)$$

$$W = \sum_{i=e,N} \frac{-q_i}{m_i} [\mathbf{p}_i - q_i \mathbf{A}_0(\mathbf{r}_i)] \cdot \mathbf{A}(\mathbf{r}_i) + \frac{q_i^2}{2m_i} \mathbf{A}^2(\mathbf{r}_i), \quad (3)$$

Fine structure constant

So purely QM

$$p = \frac{2\alpha}{9\pi} \frac{\beta_{OR}^{D/L}}{\alpha_E} \left(\ln \left(\frac{m_N}{m_e} \right) + 1 \right) eB \quad \longrightarrow \begin{array}{l} \text{2-octanol in 10 T: } V = 0,6 \text{ nm/s} \\ \text{(experimental challenge!)} \end{array}$$



The magneto-chirodynamical effect

$$\vec{p} = \zeta^{D/L} \vec{B} \quad \longrightarrow \quad E_{kin} = \frac{(\zeta^{D/L} \vec{B})^2}{2m_N}$$

Where does the energy come from? Field or quantum vacuum?

Considerations:

- The momentum can only come from the QV, B has no momentum
- One can extract energy from the QV; cf. Casimir effect

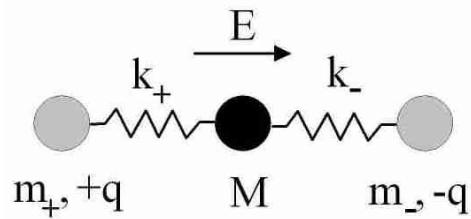
Conjecture:

E_{kin} is supplied by the source of the magnetic field, necessary to create the vacuum corrections to the magnetization of the molecule (~ “magnetic Lamb shift”)

The second magneto-chirodynamical effect

$$\vec{p} = \zeta^{D/L} \partial^2 \vec{B} / \partial t^2$$

This effect is symmetry allowed, and has a classical explanation:

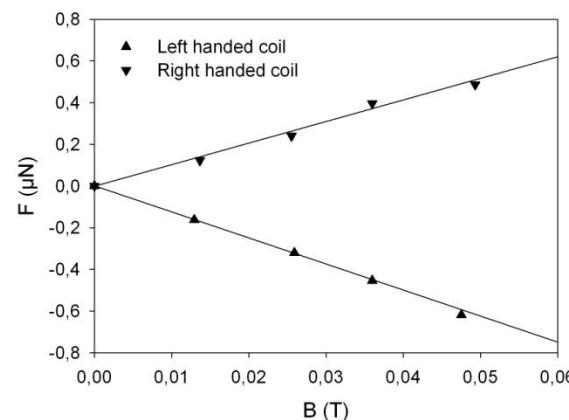
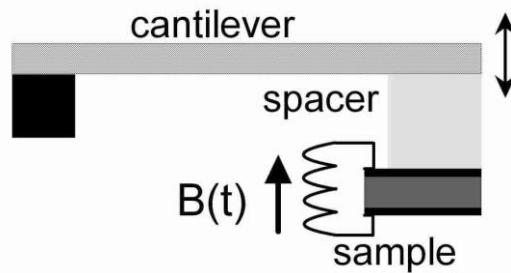


The electric displacement current in a dielectric also carries mechanical momentum. Driving the displacement current with an induced voltage gives

$$J_D = \chi \epsilon_0 \partial E / \partial t$$

$$E = \zeta^{D/L} \partial B / \partial t \quad \longrightarrow \quad p = \chi \gamma \epsilon_0 \zeta^{D/L} \partial^2 B / \partial t^2$$

$$p_D = \gamma J_D$$





The magneto-chirodynamical effect in other areas:

High energy physics:

Chiral magnetic effect for relativistic fermions:

$$\mathbf{j} = \alpha (\mu_L - \mu_R) \mathbf{B}$$

e.g. Prog. Part. Nucl. Phys. 75, 133 (2014)

Condensed matter physics:

Chiral magnetic effect in Weyl semimetals: Li et al, Nature Physics 2016



Chiral electronics ?!

Conclusion

Symmetry arguments are a powerful instrument to discover new effects, in magnetic fields or elsewhere

There are still plenty of undiscovered magneto-chiral effects out there.