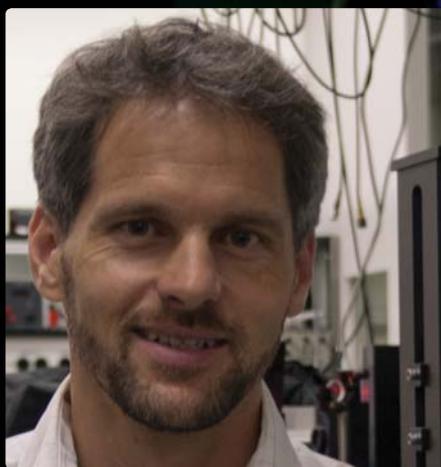


# Spectroscopics explained

Ultrafast spectroscopic methods can provide information on light-induced chemical reactions at the atomic level. **Dr Jan Helbing**, of the University of Zurich's Institute of Physical Chemistry, has focused much of his career on exploring and improving these techniques to great effect



**Firstly, can you tell us how working in Professor Majed Chergui's (see p81) group from 1997-2002 influenced your work? Do you continue to collaborate with Chergui?**

Majed's group was a unique place for many of his scientific friends and leading figures in the physical sciences to interact. Experiencing the scientific and human diversity of this community greatly influenced me, encouraging me to pursue a scientific career.

What I realised from my own work was the need to expand our toolbox for the investigation of ultrafast processes, which was a key motivation in joining Peter Hamm's group for postdoctoral research. In Lausanne, I also witnessed the beginnings of transient X-ray absorption spectroscopy. This helped me believe in the final success of, initially very difficult, experimental developments.

**What are transient vibrational circular dichroism (VCD) signals and why were they so difficult to observe before your work?**

Transient VCD signals are still very difficult to observe! A static VCD spectrometer needs to detect a difference in sample

transmission between left- and right-handed polarised light of  $10^{-3}$ - $10^{-5}$ . In a transient VCD experiment, we now want to measure small changes of that difference provoked, for example, by previous excitation with a visible laser pulse. Not only does that result in a very tiny double difference, but we also have to be able to distinguish this desired chiral signal from the background of other achiral signals, which are often much larger.

**Why are ultrafast lasers so important to chiral spectroscopy?**

Beyond the obvious advantage of allowing studies with very high time resolution, ultrafast lasers may become very useful for 'conventional' chiral infrared (IR) spectroscopy, as they constitute very bright light sources with a large bandwidth. Many highly sensitive detection schemes employed by instruments for ultraviolet and visible light have so far not been used in the IR band, because conventional thermal light sources are not sufficiently strong, and IR detectors are not sensitive enough. It is clear that a successful transient VCD spectrometer will eventually need to be at least one order of magnitude more sensitive than current static VCD apparatus. This will reduce the detection limit and integration time for routine measurements.

**How do quantum chemistry calculations combine with measurements in your experiments? Is there room for improvement regarding accuracy in both measurements and calculations?**

In direct connection with chiral spectroscopy we only employ standard quantum chemistry code for the prediction of static VCD spectra, mainly for the determination of absolute configurations as a service to external users of our commercial spectrometer. The ability of VCD to pinpoint structures of flexible molecules in solution could be better if solvent effects were predicted with improved

accuracy. This will certainly become an even bigger challenge in the simulation of transient VCD signals.

It is a great advantage that femtosecond experiments and computer simulations 'operate' on the same timescale. Nevertheless, the sensitivity of nonlinear IR spectroscopy to small spectral shifts and intensity changes is currently far greater than the accuracy of even the best *ab initio* techniques. On the other hand, linking an experimental signal to a specific chemical event can often be very difficult. The challenge is always to identify a common, robust observable.

**Whilst the focus of your research is on developing chiral spectroscopic techniques, are there any significant findings regarding molecular structure or the conformation of biomolecules that you have made using your technique so far?**

So far we have not made any real new discoveries using time-resolved chiral spectroscopy because the technique is not yet sensitive and reliable enough to study, for example, photo-induced conformational changes in biomolecules. Within the next few years, I expect transient VCD or vibrational rotary dispersion (VORD) to become useful for resolving structural transitions of smaller, and less flexible, molecules.

**How important is fostering young research talent to you? What is the best way to motivate people starting out in a postgraduate career?**

My own group is very small, meaning that I can always be in very close direct contact with my collaborators and their projects. It is very important for me that graduate students have the opportunity to present their work at international conferences as early as possible, and that they develop a feeling of responsibility and 'ownership' of their results.

# Spectroscopy **with a twist**

The wide-ranging methods encompassed by spectroscopy afford a number of diverse scientific advantages. Some can provide detailed information about molecular structure, while others allow us to unravel the mechanisms of chemical reactions with high time resolution. A team from the **University of Zurich** is conducting extensive research to extend the spectroscopic toolbox in order to better achieve both at the same time

**FEW OTHER EXPERIMENTAL** observables can today be computed with better efficiency and accuracy by *ab initio* quantum mechanical calculations than vibrational spectra. A key element for the structure sensitivity of infrared spectroscopy is the close relationship between the localised motions of atoms and charge with the orientation of the vibrational transition dipole moments. Scientists are able to read out this orientation with the help of polarised laser light, using a combination of light fields to measure angles between different transition moments. As a result, the relative orientations of different parts of a molecule and their changes during chemical reactions can be mapped out.

One example of this is transient two-dimensional infrared (2D-IR) spectroscopy, a relatively new technique which boasts many advantages over other methods. 2D-IR can, for example, measure anharmonic couplings between modes and energy flow between different parts of a molecule. While its spatial resolution is usually only modest in comparison with X-ray diffraction or nuclear magnetic resonance (NMR), it affords much higher, femtosecond time resolution. However, this high time resolution can only be fully exploited when it is possible to record 2D-IR spectra during ultrafast non-equilibrium events, such as photo-triggered reactions and conformational changes. Unlike conventional 1D transient absorption methods, transient 2D-IR can directly detect distance and orientation changes between two molecular units or correlate the vibrational transitions of educts and products of a photochemical reaction.

In a similar way, circular dichroism spectroscopy is highly sensitive to the absolute configuration and conformation of chiral molecules but is usually only used for equilibrium experiments. Today, however, laser technology is sufficiently advanced to enable the recording of chiral signals with ultrashort light pulses. It is therefore unsurprising that time-resolved chiroptical spectroscopy is currently undergoing a renaissance. Lying at the heart of its progressive

development and experimentation is the work of Dr Jan Helbing and his colleagues at the University of Zurich in Switzerland.

## THE HELBING LABORATORY

In Helbing's opinion, although the high information content of vibrational spectra has been known for a long time, it is still too little exploited in ultrafast spectroscopy. Thus, research and expansion of knowledge in this scientific area is a fundamental aim in the Helbing Laboratory. The team's key objective is to make polarised IR spectroscopy more universally useful by pushing the detection limits, improving the signal-to-noise ratio and by exploring new observables in chiral and nonlinear measurements. Helbing outlines the most frequent reason for this lack of exploitation: "There is a lack of sensitivity, but also insufficient spectral resolution due to band overlap". In light of this, the project is seeking to redress the balance through their extensive research.

Such an ambitious goal requires the Helbing Laboratory to collaborate with other researchers in different fields, institutions and organisations, all of which provide valuable diversity to their research. The high degree of specialisation required to develop and operate the team's setups makes collaboration with experts in chemical synthesis, material design and theory an indispensable feature of their work. Such an approach ensures that Helbing's dream of putting the team's instruments to meaningful scientific use can be realised. For example, in the past the lab has benefited from the synthesis of peptides with integrated photo switches, both by the in-house Institute of Organic Chemistry and by universities abroad, helping them to explore the structure resolution power of transient 2D-IR spectroscopy and to learn about the details of conformational transitions of turn motifs. Currently, the University of Zurich researchers are collaborating with Italian and Japanese laboratories, capable of making special light-sensitive chirality switches.

## INTELLIGENCE

### TIME-RESOLVED VIBRATIONAL CIRCULAR DICHROISM AND VIBRATIONAL ROTARY DISPERSION SPECTROSCOPY

#### OBJECTIVES

To continue to develop ultrafast spectroscopic methods – particularly vibrational circular dichroism and vibrational rotary dispersion – which are both structure-sensitive and fast enough to gain direct information about the rearrangement of atoms in light-induced chemical reactions.

#### KEY COLLABORATORS

PhD students:

**Biplab Dutta; Julien Réhault**, University of Zurich, Switzerland

Other:

**Professor Peter Hamm**, University of Zurich, Switzerland

**Professor Massimo Olivucci**, University of Siena, Italy and Bowling Green State University, Ohio, USA

**Professor Kazuto Takaishi**, Seikei University, Tokyo, Japan

#### FUNDING

Swiss National Science Foundation

Werner Legacy of the University of Zurich

University of Zurich

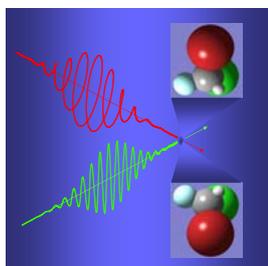
#### CONTACT

**Dr Jan Helbing**  
Group leader

Universität Zürich  
Physikalisch Chemisches Institut  
Winterthurerstrasse 190  
CH-8057 Zürich, Switzerland

T +41 44 635 44 71  
E jhelbing@pci.uzh.ch

**DR JAN HELBING** completed his PhD in 2001 as a member of Professor Majed Chergui's group at the University of Lausanne, for which he was awarded the Prix Brunner. Early in 2002 he took a postdoctoral position in Professor Peter Hamm's group at the University of Zurich, developing the new technique of transient two-dimensional infrared spectroscopy. In 2004 he became Oberassistent at the Institute of Physical Chemistry in the University of Zurich and has been a tenured Research Associate and Lecturer since 2011.



## CHIRAL VIBRATIONAL SPECTROSCOPIES

Chiral vibrational spectroscopies, such as vibrational circular dichroism and vibrational rotary dispersion, have a number of experimental uses and are central to the research taking place at the Helbing Laboratory. Importantly, they have key roles in a diverse number of scientific areas of interest.

Vibrational spectra have been used over many years to characterise chemical compounds, due to the characteristic frequencies of different structural motifs and functional groups. For chiral molecules, the bands in the IR spectra also have slightly different amplitudes when measured with left- and right-handed circular polarised light. This difference is called vibrational circular dichroism (VCD). VCD spectra typically consist of a series of characteristic positive and negative peaks, which can today be reliably predicted by standard quantum chemistry programs. The sign of the VCD bands depends very sensitively

Although the high information content of vibrational spectra has been known for a long time, it is still too little exploited in ultrafast spectroscopy

on molecular structure and it is opposite for two enantiomers. VCD measurements are therefore mainly used to determine the absolute configuration of organic molecules in solution, for example, without having to grow crystals and record diffraction patterns. This can be of great importance for the fast characterisation of new compounds in the pharmaceutical industry.

Comparison between calculations and measurement can also provide information on conformational distributions or preferences. For biomolecules, especially peptides and proteins, secondary structure motifs may be identified. In particular, fibril formation was shown to give rise to very strong and characteristic VCD signals. Unlike optical rotation in the visible spectrum, the vibrational analogue in the IR band – vibrational rotary dispersion (VORD) – is not measured very frequently. In fact, because of causality, a VORD spectrum contains essentially the same information as a VCD spectrum. In combination

with lasers, VORD detection may, however, have some practical advantages.

## INCOMING RESULTS

The VCD results produced by the Helbing Laboratory so far have had picosecond time resolution. Initially, the team cut out narrow frequency slices from their femtosecond laser pulses to achieve better spectral resolution with single element detectors. However, since these initial stages of development, both multichannel and time-domain interferometric detection schemes have been demonstrated for static VCD and VORD measurements. In principle, they allow scientists to achieve the same time resolution as in 'conventional', achiral time-resolved IR spectroscopy. However, time resolution is currently not the main challenge for transient VCD, where it is still a struggle to reliably isolate the desired signal. Many interesting reactions take place on slower timescales, but femtosecond pulses remain useful because of their large bandwidth.

Moving on from this, it is feasible that the future might see a number of different experimental approaches. For example, given recent advances in the prediction of chiral Raman spectra, there should be a lot of interesting information to be gained from chiral transient Raman optical activity (ROA) measurements; particularly since lower frequency vibrations can be accessed. However, unlike VCD, ROA instrumentation for steady-state measurements already employs laser light and the technique will not necessarily gain sensitivity when combined with ultrashort lasers. Needless to say, this highly specialised development will be largely left to experts in (ultrafast) Raman spectroscopy.

## PLANS FOR THE FUTURE

The direction in which the collaborators intend to extend their research is a logical step – further development of their current methods. "My personal dream is to be able to monitor the equilibrium fluctuations of molecules, which are considered achiral because the exchange between two chiral configurations takes place on a very fast timescale," reveals Helbing. Together the group is planning to pursue a combination of multi-dimensional and chiral spectroscopies. The idea is to spread out a VCD spectrum in two dimensions, just as is done in 2D-IR and 2D-NMR spectroscopy. There are also several theoretical studies which indicate that these spectra would facilitate the identification of protein conformations, with enhanced sensitivity.

