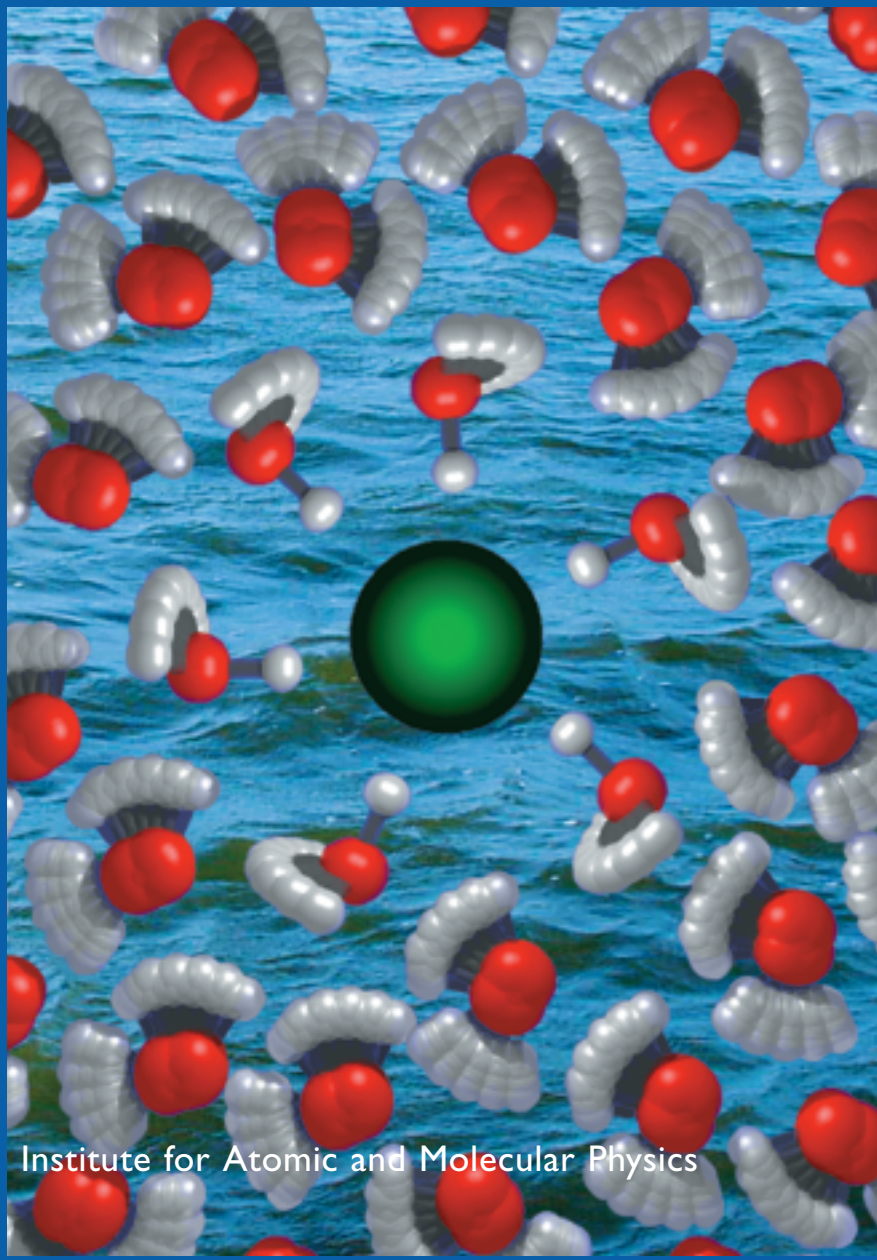
AMOLF
visitors guide



Institute for Atomic and Molecular Physics

October 2003

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Cover: The figure shows an iodide ion solvated by water molecules in liquid solution. Recent femtosecond mid-infrared experiments demonstrated that the water molecules in the first solvation shell of the ion have much slower dynamics than the water molecules outside this shell. The water molecules in the shell show translational (hydrogen-bond stretching) and reorientation dynamics with time constants of 18 and 10 picoseconds, respectively. Outside the shell these time constants are only 0.5 and 2.6 picoseconds. The figure is an artist's impression of a picture of the liquid taken with a shutter time of 4 picoseconds.

A.W. Omta, M.F. Kropman, S. Woutersen and H.J. Bakker: Negligible effect of ions on the hydrogen-bond structure in liquid water. Science 301 (2003) 347-349.
M.F. Kropman and H.J. Bakker: Dynamics of water molecules in aqueous solvation shells. Science 291 (2001) 2118-2120.

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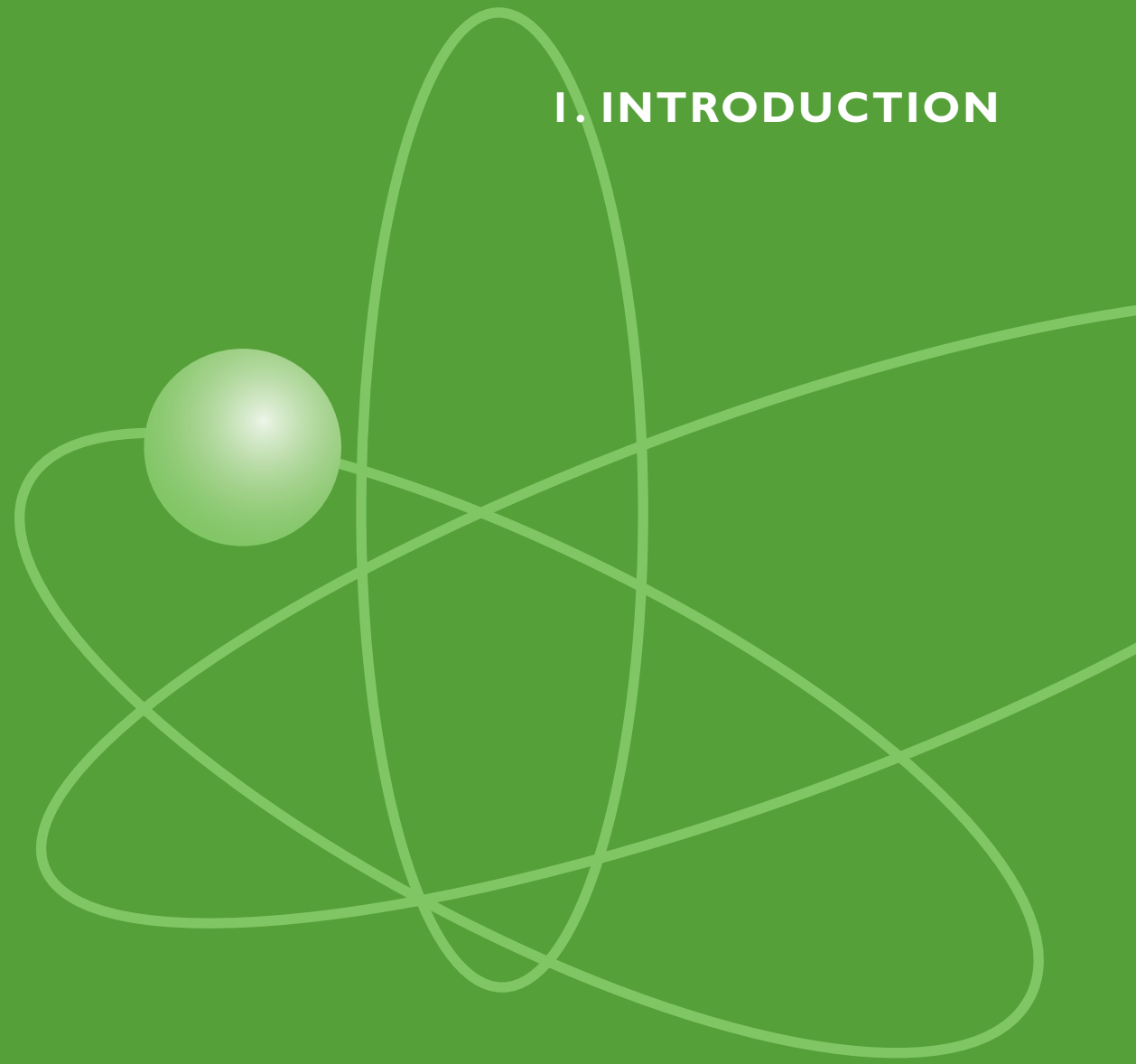
1. INTRODUCTION



AMOLF, the Institute for Atomic and Molecular Physics, is one of the five research institutes of the Dutch Foundation for Fundamental Research on Matter (FOM). The institute was founded in 1949 to separate isotopes by electromagnetic separation methods. When the institute moved to the current building in 1960, it had 69 employees. Nowadays the institute houses approximately 180 employees and a number of guest scientists. The current research at AMOLF focuses on three areas: femtosecond dynamics of matter, life science inspired physics and nanophysics. With an annual budget of about 10 million euro, AMOLF yearly publishes about 120 scientific papers, of which 15 in Physical Review Letters, Nature or Science. Every year about 10 of AMOLF's students obtain their PhD degree from one of the 7 universities where 14 AMOLF staff members hold a professorship.

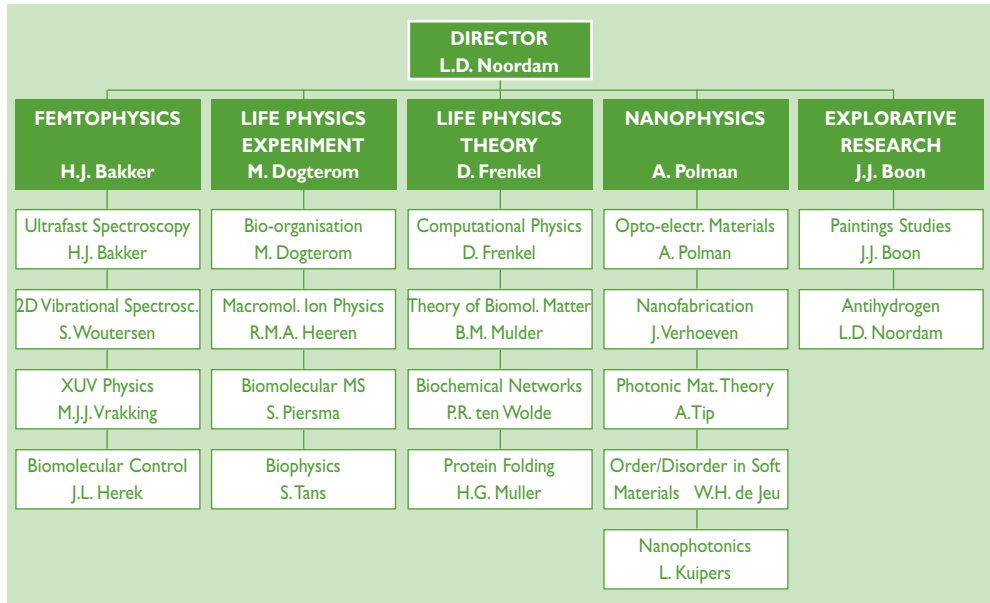
Research

AMOLF's research program is organized within five divisions:

1. **Femtophysics**: investigation and control with femtosecond pulses of the ultrafast dynamics of molecular systems, in particular of their low-frequency degrees of freedom like hydrogen bonds, molecular rotations and conformational motions;
2. **Experimental Life Science inspired Physics:** probing the structure, functioning and evolution of cells or parts thereof by advanced physical techniques such as optical tweezers and mass spectrometers;
3. **Theoretical Life Science inspired Physics:** development and application of theoretical and computational methods to model the cooperative behavior of biological systems and biomaterials;
4. **Nanophysics:** the study of optical phenomena with advanced optical probing techniques in thin-film materials made using nanoscale fabrication;
5. **Explorative research** that includes the study of physical and chemical changes in paintings, and research on the creation of antihydrogen.

Organization and Personnel

AMOLF is an institute of approximately 100 scientists, 50 technical engineers and 25 supporting staff with an average age of 36 years. An important goal of the institute is the training of scientists and technical engineers for advanced research. The organizational chart of the research groups has only a few layers: the basic unit is the research group. Such a group has one staff member (group leader) and typically 5 junior scientists (post-docs and PhD students). The group leader, being a starting project leader or a senior professor, has the scientific responsibility of the research in the group. Staff members typically spend 10-15 years at AMOLF, giving AMOLF the possibility to explore new directions by appointing 1-2 new group leaders per year. While equipment is owned and maintained by individual groups, sharing of equipment is strongly encouraged. The five department heads represent the research groups in the management and have a limited number of administrative responsibilities.



Output

In 1950, Jacob Kistemaker published an article in *Physica* entitled "Investigations on a magnetic ion source I". Since then, 4000 articles and 300 theses have been published by AMOLF researchers. Over the past five years, 130 papers per year appeared in peer-reviewed journals. Each year 10 -15 articles appear in *Physical Review Letters*, and two to three articles in *Nature or Science*. In addition, around ten PhD students defend their theses each year. Recent highlights and a complete list of AMOLF's publications can be found at www.amolf.nl.

An important part of AMOLF's mission is to transfer knowledge to industry, or society in general. Indeed, several of AMOLF's research groups carry out research projects with industrial partners and quite regularly ideas, materials, or technology developed at AMOLF, lead to the development of commercial products.

About this visitors guide

This guide provides a first introduction to the institute for visitors and those considering joining AMOLF. In the first part the research of the nineteen research groups at the institute is presented. In subsequent chapters the support groups are introduced, and practical information is given such as how to apply and how to get to AMOLF. Further information about AMOLF can be found at www.amolf.nl. We hope you will enjoy reading the visitors guide and look forward to seeing you at AMOLF.

Bart Noordam
Director

2. RESEARCH

2.1 FEMTOPHYSICS

2.1.1. ULTRAFAST SPECTROSCOPY
H.J. Bakker

This group studies the molecular structure and dynamics of hydrogen-bonded systems in the condensed phase with ultrafast, nonlinear spectroscopic techniques.

Hydrogen bonding plays an essential role in the dynamical and structural properties of condensed-phase systems like liquid water. Unfortunately, for most hydrogen-bonded systems, the dynamics cannot be studied with linear spectroscopic techniques like infrared absorption or Raman spectroscopy, because the absorption lines are strongly inhomogeneously broadened. Hence, dynamical and microscopic structural information can only be obtained with *nonlinear* optical techniques that allow the selective measurement of the response of a subensemble. Examples of these techniques are saturation spectroscopy, spectral-hole burning and photon-echo spectroscopy. These techniques require the availability of intense, ultrashort laser pulses of which the central frequency can be tuned to the resonance frequency of molecular vibrations (mid-infrared, 2.5-10 μm) and/or hydrogen bonds (far-infrared, 50-300 μm). In addition to these conventional nonlinear spectroscopic techniques, we are now also developing time-resolved single-molecule spectroscopy.

In recent years, we studied the molecular structure and dynamics of pure liquid water (H_2O) and isotopically diluted water (HDO dissolved in D_2O and HDO dissolved in H_2O). In these studies intense femtosecond laser pulses with a central wavelength of 3 μm (resonant with the O-H stretch vibration) and 4 μm (resonant with the O-D stretch vibration) were used. We studied the time scale on which the hydrogen bonds stretch and contract, i.e. the time on which the water molecules move with respect to each other. For liquid water, we found a characteristic time scale of 400 femtoseconds, for deuterated water of 500 femtoseconds. We also observed that these hydrogen-bond stretching dynamics are strongly coupled to the reorientational motion of the water molecules. This coupling turns out to be responsible for the non-Arrhenius character of the temperature dependence of the molecular reorientation. In addition, we studied the vibrational energy relaxation of the O-H stretch vibration of HDO and H_2O. The vibrational lifetime of the O-H stretch vibration is much longer for HDO (approximately 740 femtoseconds at 300 K) than for H_2O (approximately 260 femtoseconds at 300 K). The reason for this is that for H_2O the O-H stretch vibration is in resonance with the overtone of the H-O-H bending mode, whereas for HDO there is a large energy mismatch between the O-H stretch and the overtone of the H-O-D bending mode. Both for HDO and H_2O the vibrational lifetime shows an anomalous dependence on temperature, i.e. the lifetime becomes approximately 20% *longer* when the temperature is increased from room temperature to the boiling point.

We also found that the O-H stretch vibrational potential of water is extremely anharmonic as a result of the strong hydrogen-bond interaction (Fig. 1). Due to this anharmonicity, the hydrogen atom of the O-H bond can be transferred to the hydrogen-bonded partner molecule by exciting the molecule to the *second* excited state of the O-H stretch vibration. Since this transfer takes place leaving the electron behind, an H_3O^+-OH^- contact ion pair is formed. The formation of this ion pair is the first step of the spontaneous autodissociation reaction of water. Up to now, the contact ion pairs were believed to result from water molecules being strongly squeezed together. However, from the present results it

follows that spontaneous thermal excitation to the *second* excited vibrational state forms a far more efficient route to form these ion pairs (Fig. 2).

Recently, we studied the dynamics of water molecules in the solvation shells of ions. Aqueous solvation plays a crucial role in chemical reactions and in the determination of the three-dimensional structure of large complicated structures like proteins. The vibrational lifetime of the O-H stretch vibration of HDO molecules in the first solvation shell of the halogenic anions Cl^- Br^- and I^- was observed to be 2.6, 3.3 and 3.6 picoseconds, respectively. These lifetimes are much longer than the vibrational lifetime of bulk HDO molecules. As a result, after a few picoseconds only the response of the solvating water molecules is observed, which enables a detailed, selective study of the dynamics of these molecules. We found that water molecules in the solvation shells of Cl^- Br^- and I^- anions show 20-50 times slower hydrogen-bond dynamics and 3-6 times slower orientational dynamics than bulk water. This shows that the solvation shells of these anions are very rigid.

Investigators: F. van den Broek, A. Lock, M. Kropman, A.W. Omta, D. Madsen, Y. Rezus, and J. Gilijamse.
Technical support: H. Schoenmaker, R. Kemper and A. Buyserd.
H.J. Bakker is also professor of physical chemistry at the University of Amsterdam.

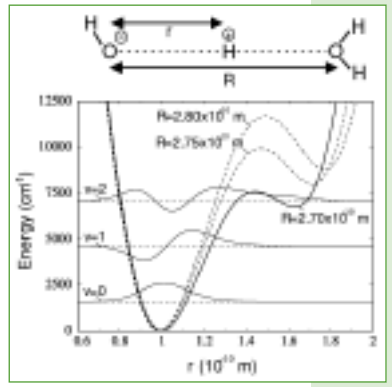


Fig. 1: Anharmonic vibrational potential of the O-H stretch vibration of a water molecule that is hydrogen-bonded to another water molecule. In the second excited vibrational state, the hydrogen atom gets strongly delocalized between the oxygen atoms of the two water molecules.

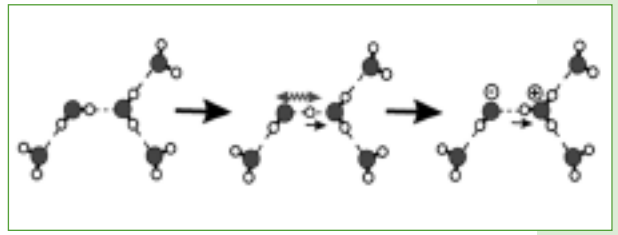


Fig. 2: Schematic picture of the autodissociation of water. The O-H stretch vibration of a water molecule gets excited by spontaneous thermal fluctuations. The strongly delocalized quantum character of this state induces the transfer of a proton to the hydrogen-bonded partner molecule, which leads to the formation of an H_3O^+-OH^- contact ion pair.

2.1.2 TWO-DIMENSIONAL VIBRATIONAL SPECTROSCOPY
S. Woutersen

In this research project we investigate ultrafast conformational dynamics in solution by means of nonlinear vibrational spectroscopy.

The chemical activity of biomolecules is intimately related to their secondary and tertiary structure (conformation). In solution, conformations are not static, but fluctuate as a consequence of the strong interactions with the surrounding solvent molecules. Conformational dynamics take place on many different time scales, ranging from seconds (folding of proteins) to picoseconds and less (hydrogen-bond fluctuations, rotations of sidegroups). The dynamics occurring on slower time scales (down to nanoseconds) can be investigated with many different experimental methods, including nuclear magnetic resonance (NMR) spectroscopy and time-resolved X-ray diffraction. The picosecond and subpicosecond time scales are more difficult to access with conventional experimental methods. For these very fast time scales the methods of nonlinear vibrational spectroscopy are very well suited.

The idea behind multi-dimensional nonlinear vibrational spectroscopy is to apply the methods originally developed in NMR to nonlinear optical excitations of vibrational transitions. These vibrational transitions can be resonantly driven by excitation in the mid-infrared wavelength region. Multi-dimensional vibrational spectroscopy can be used to study both structure (by measuring couplings between vibrations) and dynamics (by measuring relaxation processes).

Structural information is obtained from two-dimensional (2D) pump-probe spectroscopy (see Figure). In such an experiment, an intense pump pulse is used to excite a particular vibrational mode, and a probing pulse to investigate the response of the molecule at a different frequency. The response is measured as a function of both frequencies ν_{pump} and ν_{probe}. Excitation of one mode leads to a response at the frequency of the other when the two vibrations are coupled. This coupling is observed as an off-diagonal peak in the 2D spectrum. From the intensity and anisotropy of the off-diagonal peaks the distance and orientation between the vibrating chemical bonds can be derived. The time resolution of the method is determined by the duration of the pulses, which is less than a picosecond.

Fluctuations of the conformation give rise to relaxation processes in which the vibrational energy is transferred between coupled modes. This transfer of excitations can be observed and is directly related to fluctuations of specific degrees of freedom of the molecule. The time scale to which this method is most sensitive is determined by the inverse of the frequency difference between the two modes. For vibrational transitions this is typically on the order of 100 femtoseconds. Nonequilibrium conformational dynamics can be studied by optically triggering a change in the conformation, and recording 2D spectra as a function of the delay with respect to the optical trigger pulse. In this way, it should be possible to construct a movie of the conformation as a function of time.

We are currently performing experiments on several molecular systems. In experiments on Watson-Crick A:U basepairs (a cooperation with G. Cristalli, University of Camerino, Italy), we study the dynamics and correlation of the two hydrogen bonds involved in basepair formation. In studies on

DNA oligomers in aqueous solution, we focus on conformational fluctuations. Optically triggered structural changes will be studied in diarylethene-based molecular photoswitches, which are promising candidates for optical data storage (a cooperation with the group of T. Jovin, MPI Göttingen).

Research staff: O. Larsen.
Technical support: H. Schoenmaker and R. Kemper.

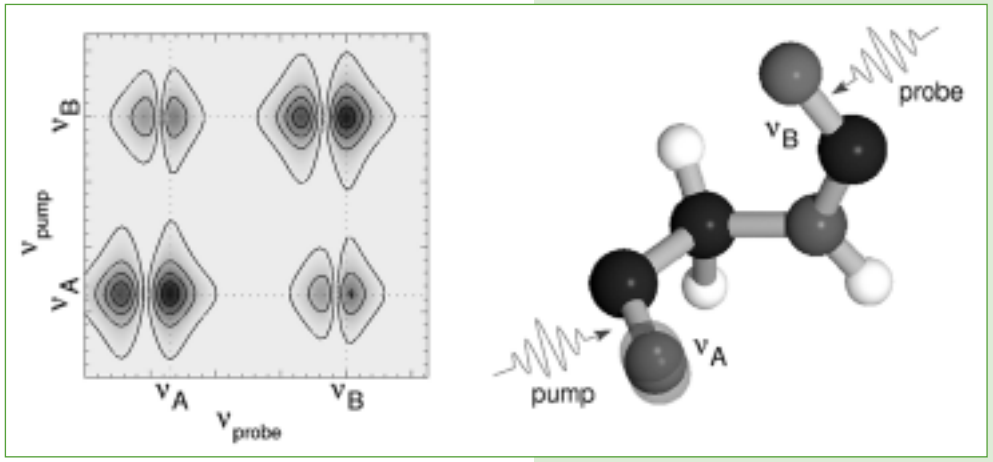


Fig. 1: Schematic representation of two-dimensional spectroscopy. The intensity of the cross-peak at (ν_A,ν_B) is proportional to the strength of the coupling between modes A and B. From the coupling strengths the conformation can be deduced.

2.1.3 XUV PHYSICS
M.J.J. Vrakking

The XUV Physics Group at AMOLF studies the control of atomic and molecular properties using tailored femtosecond laser pulses, with an emphasis on strong field phenomena like high harmonic generation, alignment of molecules and Coulomb explosions of clusters. Our aim is to gain fundamental insight into the atomic, molecular and cluster-laser interactions, to improve control schemes and investigate their fundamental limitations, and to develop useful 'products', like optimized XUV sources and samples of aligned molecules.

(A) Control of the formation of attosecond laser pulses in high harmonic generation (collaboration with H.G. Muller)
To study electron dynamics in *real-time*, attosecond pulses (1 as = 10^{-18} seconds) are needed. Attosecond laser pulses can be generated in high harmonic generation (HHG). Here, electrons are ionized and accelerated by an intense laser before being driven back towards the ion core where they originate and where recombination can lead to the generation of extreme-ultraviolet (XUV) photons. Experiments in Paris and at AMOLF have recently demonstrated 250 attosecond XUV pulses (see Figure 1). Sofar these pulses are formed in trains, where one pulse appears at every intense half-cycle of the driver laser. Future research is aimed at reducing the length of these trains to an *isolated* attosecond pulse, extension of the angularly resolved photoelectron imaging technique developed to characterize the attosecond pulses and applications in time-resolved experiments. AMOLF is the coordinator of a new European Research Training Network (XTRA) on the development and application of ultrashort XUV pulses for time-resolved and non-linear applications.

(B) Control of the external degrees of freedom of molecules in an intense laser field
Molecules in intense laser fields align their internuclear axis to the polarization axis of the laser. This 'dynamic alignment' is one of the prime examples of the emerging field of 'molecular optics', where intense lasers are used to control internal and external degrees of freedom of atoms and molecules. Sofar most research has concentrated on alignment of molecules with the strong laser field present. However, the laser can also excite a rotational wavepacket that leads to alignment after the laser pulse is gone. Recently, the first demonstration of this *field-free* alignment was obtained at AMOLF (Phys. Rev. Lett. 87, 153902 (2001)). There are many applications in physics and chemistry where field-free aligned molecules may be used advantageously.
We believe that molecular alignment can be much better controlled using properly shaped laser pulses. Building on recent numerical simulations, future research will involve optimal control experiments using an evolutionary algorithm to determine the optimum pulse shape for field-free alignment.

(C) Control of the generation of X-rays in femtosecond laser-cluster interactions
In high intensity laser physics, clusters represent a unique intermediate between isolated gas phase atoms/molecules and solid materials. A wealth of fascinating physical phenomena occur in clusters, including the production of highly charged atomic fragments and keV electrons, x-ray photons and even neutrons. Laser cluster interactions are one of approaches currently being considered to achieve a production tool for EUV lithography.
Recently we have performed optimal control experiments on the irradiation of Xe clusters with shaped femtosecond laser pulses where the optimum pulse shape for the production of highly-charged ions was determined to be a sequence of two pulses with a time delay of typ. 0.5 psec. In the future we will study mass-selected rare gas clusters and optimal control of the yield of soft x-ray photons.

(D) Imaging of (sub)-meV electrons: Photoionization Microscopy
The study of electron dynamics is also interesting in slowly varying or DC electric fields. In 2D imaging of electrons formed by threshold photionization, we have shown how direct and indirect photoionization events can be distinguished (Phys. Rev. Lett. 85, 4024 (2000)), and that a quantummechanical interference can be observed between several competing trajectories that take the electron from the atom to the detector (see Figure 2, Phys. Rev. Lett. 88, 133001 (2002)). Future directions are the application of photoionization microscopy to hydrogen atoms and slow photoelectron imaging of low-frequency (THz) ionization, the latter being relevant to the generation of attosecond pulses (see A).

(E) Development of experimental instrumentation and methodologies
Our work requires a strong experimental infrastructure, both with regards to laser and experimental equipment. Therefore we have a continued effort to improve our experimental techniques. In particular, we have improved the capabilities of 2D imaging techniques through the implementation of new experimental geometries, data analysis algorithms and data acquisition strategies (enabling 3D imaging). Currently, we work on improving evolutionary algorithms for use in optimal control experiments, modelling of laser-molecule or laser-cluster interactions, and optimal design of scientific instrumentation.

Investigators: F. Lepine, Y. Ni, S. Zamith, T. Martchenko and P. Agostini (guest).
Technical support: A. de Snaijer, R. Kemper and A. Buijserd.

Fig. 1: Experimentally determined XUV pulse shapes using Ar, Kr and Xe as high harmonic generation medium, showing the formation of attosecond laser pulses.

Fig. 2: Experimental photoelectron image recorded in Xe, showing the presence of quantum mechanical interferences between various pathways between the atom and the detector.

Fig. 1

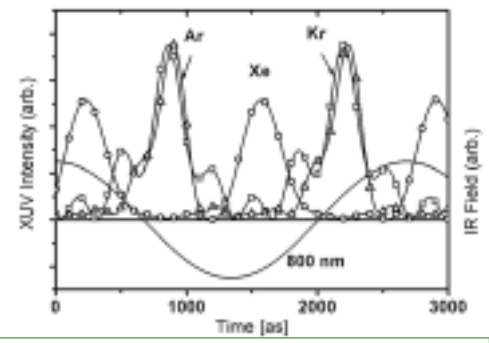
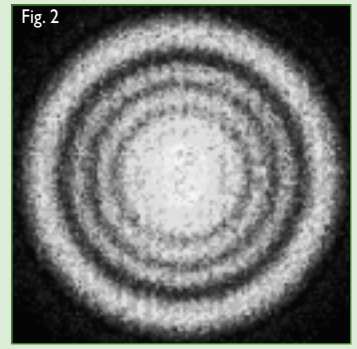


Fig. 2



2.1.4 BIOMOLECULAR CONTROL
J.L. Herek

The aim of this new research group, which was established in August 2002, is to probe and control ultrafast molecular dynamics in biological and biomimetic systems. The experimental approach combines adaptive femtosecond pulse shaping with molecular feedback in a learning-loop scheme.

Coherent control aims to steer a system towards a desired outcome by exploiting quantum interference effects. In a closed-loop experiment combining molecular feedback, adaptive femtosecond pulse shaping, and a genetic learning algorithm, systems considered intractable on an ab initio quantum-mechanical level may be explored. This approach works directly on the Hamiltonian of the molecular system, iteratively refining the driving optical field to achieve a chosen target objective, i.e. enhancement of a specific reaction product pathway.

We recently used this technique to demonstrate control of a biological function. In collaboration with the Max-Planck-Institute for Quantum Optics, we explored the regulation of energy flow pathways in the 125 kDa light-harvesting antenna complex LH2 from *Rhodospeudomonas acidophila*, a photosynthetic purple bacterium (see Fig. 1). In this prototype system, only 50% of the light harvested by carotenoid donor molecules is transported to bacteriochlorophyll acceptor sites; the remaining energy is dissipated via intramolecular loss channels. We found that the partitioning of excitation energy into these competing channels of energy transfer (ET) and internal conversion (IC) could be controlled by adaptive femtosecond pulse shaping [J.L. Herek *et al*, Nature 417:533-535, 2002].

We excited the carotenoid donor molecules with shaped femtosecond pulses (Fig. 2) from a non-collinear optical parametric amplifier and monitored the ensuing energy flow by probing the transient absorption kinetics of the donor and acceptor molecules. Spectrally separated, discrete signals of the IC and ET channels provided feedback for a learning loop evolutionary algorithm that optimized the excitation pulse shape for a given target. With no prior knowledge of the required driving field for affecting energy flow pathways, we began with "blind" optimizations, i.e. starting with random phase and amplitude patterns across the excitation pulse. We found that the IC/ET branching ratio could be enhanced by a complex field featuring a multi-pulse temporal structure. By restricting the optimization to solutions of pulse trains, the IC/ET ratio was more than double the natural value. The restricted optimization was based on a sinusoidal phase function applied to the pulse shaper, with only three adjustable parameters (amplitude, frequency, and offset). By shifting the offset parameter, the optical phase pattern of the excitation pulse could be varied in a controlled way, without affecting the pulse envelope, energy, or spectrum. The observation that the IC/ET ratio was modulated by changing the carrier phase pattern indicates that the control mechanism exploits molecular coherence.

Beyond the novelty of actively controlling biological function with tailored excitation light, feedback-driven coherent control strategies offer a new spectroscopic tool for extracting information from complex biosystems by providing insight to the molecular potential energy surfaces and vibrational modes relevant to specific reactions, conformational changes, and functions. We are exploring the pathways, efficiencies, and underlying factors that govern ultrafast biological reaction dynamics in relation to their function, in studies of both native and model systems designed for energy and charge transfer. Of particular interest is the role of vibrational coherence in biological reaction dynamics and function.

The laboratory houses a 1 kHz amplified femtosecond laser coupled to two noncollinear optical parametric amplifiers. The system delivers femtosecond laser pulses (< 20 fs) tunable throughout the visible and near-infrared spectral region. A prototype 2 x 640 element liquid crystal pulse shaper allows high-resolution phase and amplitude control. We are exploring a variety of biological and bio-mimetic systems by combining adaptive femtosecond pulse shaping, evolutionary algorithms, and spectroscopic techniques such as pump-probe, transient absorption, and fluorescence upconversion.

Investigators: J. Savolainen and T.A. Cohen-Stuart.
Technical support: R. Kemper, H. Schoenmaker, A. de Snaijer and N. Dijkhuizen.

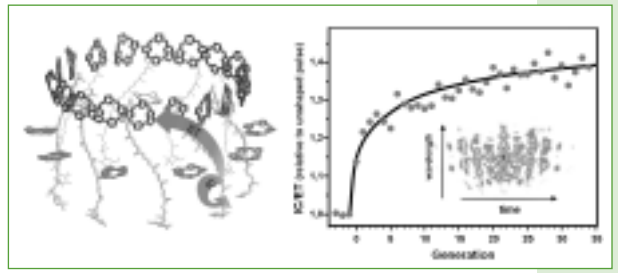


Fig. 1: Right: The LH2 antenna complex. Excitation of carotenoid molecules leads to either energy transfer (ET) to bacteriochlorophylls, or energy loss by internal conversion (IC) within the carotenoid itself. The branching ratio is 50:50. Left: With a target goal of enhancing the IC/ET ratio, the evolutionary algorithm finds a complex pulse shape (inset) that changes the branching ratio by a factor of 1.4.

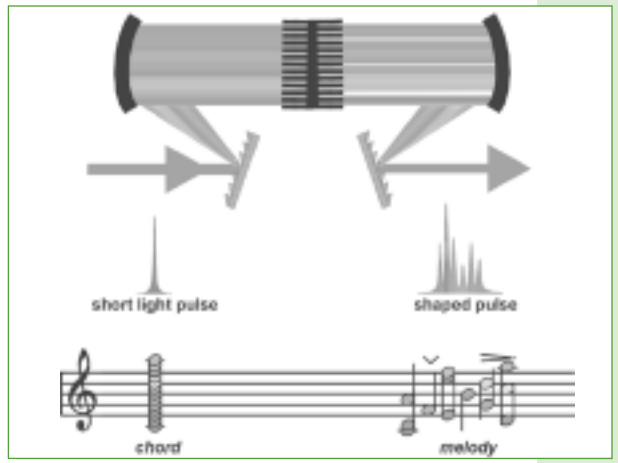


Fig. 2: Schematic of the pulse shaper. Femtosecond pulses are dispersed by a grating, and the different colors are focused onto a computer-controlled liquid crystal array. Varying the voltage on each pixel changes the phase and amplitude of each corresponding frequency component. An unshaped femtosecond pulse is analogous to a chord (where all frequencies are played at the same time), whereas a shaped pulse can be thought of as a melody.

2. RESEARCH

2.2 LIFE PHYSICS EXPERIMENT

2.2.1 BIO-ASSEMBLY AND ORGANIZATION
M. Dogterom

The group bio-assembly and organization focuses on the study of physical processes that contribute to the assembly, transport, and spatial organization of macromolecular aggregates in living cells. The aim is to unravel, through quantitative experiments under simplified conditions, the physical mechanisms underlying these processes.

Our research is centered around four projects dealing with the dynamics, force generation, and organization of microtubules, the role of motor proteins and microtubules in organizing membrane networks, and the physical mechanism of FtsZ ring contraction in the bacterium *E. coli*. In addition we work on optical trapping techniques for advanced manipulation and detection of colloidal arrays. The main projects are described in some detail below.

Growth dynamics and regulation of force generating microtubules
Microtubules are rigid biopolymers that self-assemble from tubulin proteins. The assembly of a single microtubule generates pushing forces that are used for transport processes in living cells. We study these forces using two methods: first, by letting a surface-attached microtubule polymerize against a microfabricated glass barrier and analyzing the subsequent buckling of the microtubule; second, by using a set-up involving optical tweezers where we let a microtubule grow form a nucleation site attached to a trapped bead, again in front of a rigid barrier. This last method allows detection of the growth process under load with almost molecular resolution. *In vivo*, microtubule dynamics and force generation is regulated by different classes of microtubule end-binding proteins. In our experiments we try to establish at a molecular level the operational principles of these regulators. Related to this project we are also interested in the force-generating mechanism of the contractile apparatus during cell division in bacterial cells. Constriction of the cell appears to be initiated by the contraction of a ring of FtsZ filaments, a homologue of tubulin. In collaboration with the group of Dr. T. den Blaauwen of the University of Amsterdam this process is studied in living *E. coli* cells using a combination of optical tweezers, fluorescence microscopy, and molecular biology techniques.

Organization of microtubule arrays in cells
In most animal cells microtubules are nucleated by centrosomes forming so-called microtubule asters. These asters position themselves with respect to the geometry of the cell. Positioning is believed to occur through an interplay between dynamic microtubule ends exerting forces on the cell cortex and molecular motors pulling on these same microtubule ends. In microfabricated chambers, where we specifically attach motor proteins at the periphery, we study the competition between these processes. In plant cells microtubules are nucleated in a more random fashion, and ordered microtubule arrays form just below the cell membrane. These microtubules focus into a small band known as the preprophase band prior to cell division. In collaboration with the groups of B.M. Mulder (AMOLF) and A.M.E. Emons from the University of Wageningen we investigate the possible mechanisms by which these ordered arrays form. This project involves a combination of theory, simple simulations, and *in vivo* and *in vitro* experiments.

Membrane morphologies generated by molecular motors
Membrane structures in living cells such as the Endoplasmic Reticulum (ER) and the Golgi apparatus show morphologies that differ dramatically from equilibrium lipid bilayer systems. In part, these morphologies are believed to be due to the interaction of lipid bilayers with active components such as molecular motors and dynamic microtubules. To study the morphological changes that arise due to such interactions we use an *in vitro* model system that allows us to link lipid vesicles to a network of microtubules through active motor molecules. In this model system, tubular membrane networks are formed through the action of multiple motor proteins that are apparently able to join forces without other cellular components. By combining this model system with patterned arrays of microtubules we can study the competition between plus-end and minus-end directed molecular motors in defining membrane network morphologies.

Manipulating three-dimensional colloidal arrays
In collaboration with the group of A.v. Blaaderen (AMOLF/University of Utrecht) and K. Visscher from the University of Arizona we have developed a method to trap independently-programmable patterns of colloids in two different layers using a single microscope objective. Using a second, independent objective, confocal images of the three-dimensional configuration of colloids can be made (see Figure). These structures can be used as templates (with pre-designed defects) for studies of colloidal crystallization processes.

Investigators: M. Cosentino-Lagomarsino, M.M. van Duijn, A. van der Horst, J.W.J. Kerssemakers, G. Koster, E.L. Munteanu, G. Romet-Lemonne.
Technical support: H. Bar, R. Dries.
M. Dogterom is also professor of physics at the University of Leiden.

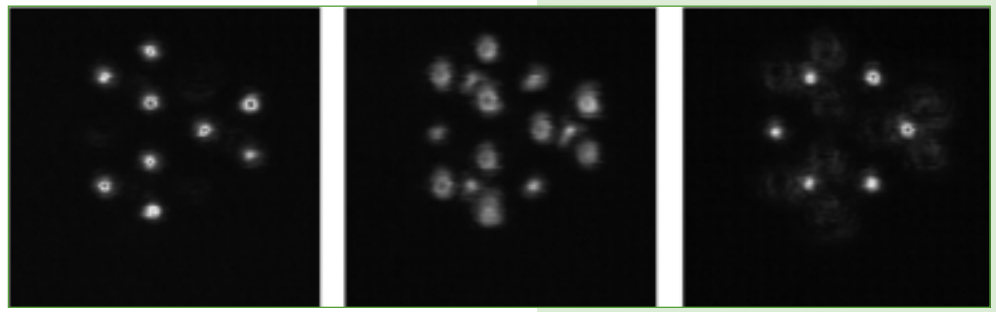


Fig.: Confocal images in 3 different planes of two trapped layers of colloids. The first layer has 9 traps (left image), and the second layer has 6 traps (right image). The middle image is taken in between the two layers and shows both patterns out of focus. Within one layer a pattern is created by time-sharing the optical trap between different computer-controlled locations. The 2nd plane is created by sending the laser beam part of the time through a alternative optical path with a different focus in the sample.

2.2.2 MACROMOLECULAR ION PHYSICS
R.M.A. Heeren

The research of the macromolecular ion physics group focuses on the development of novel mass spectrometric methodologies and techniques for the investigation of the spatial and molecular structures of macromolecules in or from complex systems to provide a link between molecular structure and biological function.

Our investigation into macromolecular structure starts at the molecular level where a wide scope of polymeric systems ranging from peptides and proteins to industrial synthetic polymers is studied with high performance mass spectrometric techniques. Key research topics include the study of fundamental processes of ion formation, ion dissociation, mass separation and detection of macromolecules to improve the derivation of structural information and to understand the binding energy relationships involved in the association of macromolecules. The next level of investigation starts when macromolecules start to form assemblies such as membranes, protein or DNA aggregates or complexes. Even further up along the research ladder various complexes start to form organelles and eventually these organelles form living cells. Continuing this line of thinking leads to the stage where groups of cells interact and form a particular spatial organization, different types of biological tissue and, finally, "living" biological systems. In our group we are using mass spectrometry to study these large macromolecules at all the different functionality levels, adapting our methodology to gain insight in the functionalities and interaction mechanisms that are markedly different for each level.

The investigation of the deposition of internal energy during collisional activation has been extended to low temperatures. An investigation of the internal energy deposition during a sustained off resonance irradiation (SORI) experiment allowed the calibration of the SORI energy scale. The studies not only determined the amount of energy input needed for dissociation, but also revealed the mechanism and amount of internal energy loss in the same experiment. For this purpose the AMOLF thermostated open cell was used of which the temperature can be varied between 80 and 450 K. Theoretical master equation modeling showed good agreement with the SORI experiments. These techniques will be employed in the physical biology project aimed at the investigation of the thermodynamics of molecular chaperone complexes in collaboration with the Free University of Amsterdam (VU) and Utrecht University.

To improve sensitivity and detection efficiency a novel RF-only quadrupole ion guide was designed and implemented on the 7T FT-ICR-MS system. Combined with the innovative PXI acquisition and control system this was the focal point of our instrumental developments. Our collaborative studies with Utrecht University on electron capture dissociation yielded new insights into dissociation mechanisms and the location of monosulfide bridges on several Lantibiotics. The location of the intramolecular monosulfide bridge could be deduced form the unusual formation of c· (radical) and z ions. For lantibiotics that contain three crossed monosulfide bridges multiple electron capture was observed but no dissociation products were formed. This mechanism is still under study.

The investigation of new imaging mass spectrometric (or mass microscopy) approaches for the study

of the spatial distribution of molecules at biological surfaces has experienced several breakthroughs recently. The Bio-TRIFT, the instrument developed for stigmatic ion imaging has been equipped with a new UV laser desorption source and has demonstrated that large biomolecules up to carbonic anhydrase (~30 kDa) can be efficiently ionised and detected. Continued Matrix Enhanced Secondary Ion Mass Spectrometry (ME-SIMS) studies demonstrated that the use of UV matrices can also enhance the production of intact molecular ions of various peptides and phospholipids. The high spatial resolution of ME-SIMS was employed to prove the existence of segregation and local ionisation effects at the surface of the matrix crystals. Similarly it was shown that local surface effects also lead to different fragmentation processes depending on the type of pseudo-molecular ion formed. This is illustrated in figure 1a and b. Figure 1a shows the optical microscopic image of a series of 2,5-dihydroxy benzoicacid crystals with phosphotidylethanolamine incorporated in them. Figure 1b is a composite image of the sodium distribution, the sodiated pseudomolecular ion and a diacylglycerol fragment ion that originated from the protonated pseudomolecular ion (see www.amolf.nl). The latter ion itself was not observed. These two figures show the effect of local crystal composition on the spectral appearance of a homogeneous phospholipid preparation. These effects can explain the occurrence of hot-spots during the commonly used MALDI ionisation technique. An investigation was started that showed how high resolution can reveal the surface topography of corrugated samples. This observation can complicate the interpretation of mass spectral images and should be accounted for in our further studies, and a theoretical study into this phenomenon was initiated. In a collaboration with the Dutch cancer institute (NKI) a study was started aimed at using imaging mass spectrometry for the investigation of the spatial-temporal behavior of cells and tissue.

All chemical imaging studies described above required new image processing tools that have been developed in the framework of the Amsterdam virtual laboratory project. At the end of 2002 during the iGrid2002 meeting these VL tools were demonstrated and tested in the distributed environment of the Dutch ASCII Cluster DAS-2.

Investigators: L.A. McDonnell, T.H. Mize, S.L. Luxembourg, A.J. Kleijnijenhuis, R. Mihalca, I.M. Taban and R. Geels.
Technical support: F. Giskes, M.C. Duursma and G.B. Eijkel.
R.M.A. Heeren is also professor phycial aspects of biomolecular mass spectrometry at Utrecht University.

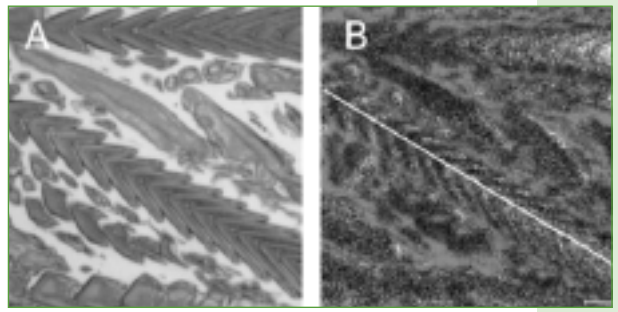


Fig. 1a: The optical microscopic image of a series of 2,5-dihydroxy benzoicacid crystals with phosphotidylethanolamine incorporated in them.
Fig. 1b: A composite image of the sodium distribution, the sodiated pseudomolecular ion and a diacylglycerol fragment ion that originated from the protonated pseudomolecular ion.

2.2.3 BIOMOLECULAR MASS SPECTROMETRY
S. Piersma

The aim of the biomolecular mass spectrometry group at AMOLF is the development of imaging mass spectrometry (MS) of biological tissues. We develop methods that allow us to map spatial distributions of biomolecules including proteins, peptides and lipids at subcellular resolution by MS.

Imaging mass spectrometry of biological tissues

Mapping the dynamic state of the proteome inside a cell or tissue is an important area in biological research. Conventionally, labelling of pre-selected molecules with a fluorescent reporter is required for molecule-specific cellular imaging using fluorescence microscopy. For direct imaging of unknown molecules a label-less method is required. In mass spectrometry the intrinsic property of molecular weight is used to distinguish molecules. Especially MALDI-ToF (Matrix-Assisted Laser Desorption/Ionisation Time-of Flight) MS can detect intact proteins and peptides with high sensitivity and selectivity over a wide mass range (10^3-10^5 Da) in complex mixtures. One of the emerging technologies in this field is imaging mass spectrometry. Recently, microprobe imaging MALDI MS of mammalian tissue has resulted in protein and peptide specific maps at 30-100 μm resolution. With this resolution tissue profiling is feasible but cellular details are not yet in reach. In order to improve the spatial resolution to subcellular lengthscales (≤1μm) both instrumentation as well as sample preparation protocols have to be developed. Development of new (high resolution) imaging ToF-MS instrumentation is pursued in the group of Heeren (see 2.2.2). We focus on improvement of the spatial resolution by designing novel sample preparation protocols.

Subcellular imaging of neuropeptides and cholesterol in snail neurons

In order to improve the spatial resolution we have combined MALDI sample preparation methods and the imaging capabilities of ToF-SIMS (secondary ion mass spectrometry) for direct molecular imaging of molluscan nervous tissue. A thin layer of 2,5-dihydroxybenzoic acid was electrosprayed on cryostat sections of *Lymnaea stagnalis* cerebral ganglia yielding micron-sized matrix crystals. The energy-moderating matrix allowed imaging of the neuropeptide APGW-amide and cholesterol. Matrix-enhanced SIMS imaging combined with electrospray matrix deposition allows direct high spatial resolution (>3 μm) molecular imaging of different classes of molecules in tissues and opens a complementary mass window (<1500 Da) to MALDI imaging mass spectrometry, but at an order of magnitude higher spatial resolution. Neuropeptide imaging is a collaboration with Drs. Jimenez and van Minnen of the department of Molecular and Cellular neurobiology at the Vrije Universiteit Amsterdam (VU).

Matrix deposition: SprayStation

Following cryostat tissue sectioning, a matrix (small organic acid: 2,5-dihydroxybenzoic acid, sinnapinic acid or α-cyanohydroxycinnamic acid.) is deposited on a tissue section in order to moderate the impact energy of the MS desorption source (ion beam or laser) and to promote efficient soft desorption/ionisation of intact biomolecules. Matrix deposition on thin tissue sections (~10 μm) should result in: (1) incorporation of surface analytes into the matrix crystals, (2) formation of microcrystals smaller than the cellular features to be observed, (3) homogeneous tissue coating by the matrix and

(4) minimal redistribution of surface analytes.
A matrix deposition set-up has been constructed based on electrospray ionization. An aerosol of micrometer sized matrix droplets is created in an electric field. Electrospray deposition facilitates analyte incorporation into the matrix and minimizes lateral diffusion over the tissue surface. In the SprayStation biological tissues can be coated reproducibly and uniformly by matrix.

Biological tissue sections

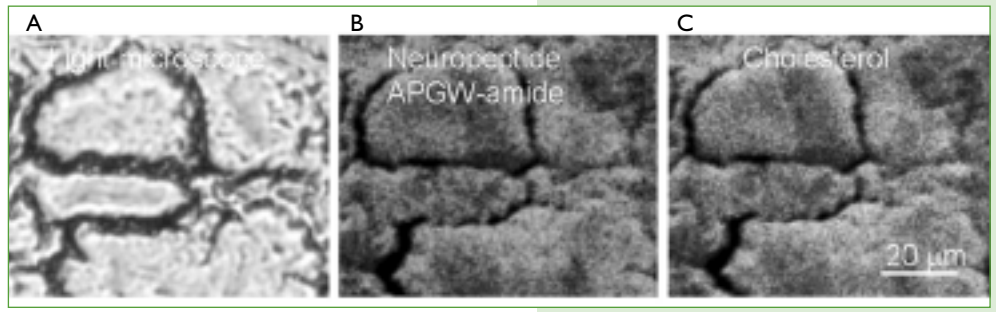
In collaboration with pathologist Prof.dr. W.J. Mooi of the Dutch Cancer Institute (NKI) tissue sections of human dermal tissue in different pathological states related to melanoma formation are studied. Method development for molecular imaging MS of complex human tissue at (sub)cellular resolution is pursued.

Protein identification

For identification of proteins targeted in imaging experiments a quadrupole time-of-flight mass spectrometer (Q-ToF) interfaced with a capillary HPLC/nanospray ionization source is used. The configuration chosen allows for semi-automated protein identification in proteolytic digests of protein mixtures. Proteins are extracted from bulk/dissected tissue material and are fractionated by liquid chromatography. Relevant fractions are screened by LC/MS and proteins are identified by MS/MS.

Investigator: A.F.M. Altelaar.
Technical support: F. Giskes and J. vd Horst.

Fig. 1: Light microscopy image and molecular images of *Lymnaea stagnalis* cerebral ganglia. Molecule specific images, selected by their molecular mass, show high similarity with the morphology seen in conventional optical microscopy. For the neurons shown, neuropeptide (B) and cholesterol (C) distributions are imaged at subcellular resolution. Both the neuropeptide as well as cholesterol are present in the cytosol and not in the nucleus.



2.2.4 BIOPHYSICS
S. Tans

The research in our group covers two themes. In the first we investigate artificial genetic networks, employing mathematical modeling and molecular biochemistry. One of our central aims is to follow and describe evolutionary processes in these model systems. Our second theme deals with molecular motors that are found in cells. We study the movements and forces produced by individual molecular complexes, principally using laser-tweezers.

Genetic Networks

Now that inventories of genes and proteins have been compiled, the following very general question is still wide-open: *How do genes, proteins, and other molecules act together to allow cells to function?* The answer cannot be found from just knowing the properties of the individual components. In stead, cellular 'know-how' only results when many components interact, generally in the form of cycles of chemical reactions, yielding rich non-linear behavior. It has recently been shown that the behavior of such networks is often intrinsically robust against small changes in their design. On the other hand, in order to survive under selective pressure, cells, and thus their decision-making networks, need to be flexible and able to change their function. A seminal question is therefore how robustness and evolvability are married in living cells. While indeed there are many hints that not only networks themselves but also the DNA code is highly dynamic -with a wide array of mutation strategies-, how these strategies play out in real survival remains extremely vague. With a physics background, our emphasis is on model systems of biochemical networks in an effort to uncover their fundamental properties. In practice, this involves synthesizing the DNA that encodes a desired network using recombinant DNA techniques and introducing it in a living cell. The behavior of the network is monitored by various techniques, e.g. by fluorescence. An integral part of our approach is to apply mathematical modeling of the networks, which is used to both design our experiments and to describe its processes quantitatively.

Protein translocation studied by laser-tweezers

A family of motors is found in cellular membranes that have the intriguing task of grabbing a folded protein, unfolding it, and transporting it across the membrane. In eukaryotes these protein translocation systems sit e.g. in membranes of mitochondrion and the endoplasmitic reticulum, in which proteins are needed but cannot be synthesized. In bacteria, similar translocation systems are present that excrete proteins to the outside, and also function to incorporate proteins in the membrane. Our aim is to pull with optical tweezers on individual proteins, while they are being translocated. Specifically, we will study the Sec translocation system that is found in *E. Coli.* Biochemical research on this model system has yielded impressive knowledge on the involved components. However, further progress in our understanding crucially depends on knowing how the parts of this motor actually move. Filling in this missing piece of this fascinating puzzle is our main motivation for this study. Because protein translocation systems have not been studied before on the single-molecular level, many open questions exist: Does the motor indeed push the protein through like a sewing machine? What forces are being generated? How are actions of the motor correlated with protein unfolding?

Investigators: A. Adiciptaningrum, M.J.A. Tyreman, T. Kalkbrenner, R. van Leeuwen, F. Poelwijk and E. Riemslag.
Technical Support: H. Bar, R. Dries and A.E. Kraij-Kerkhoff.

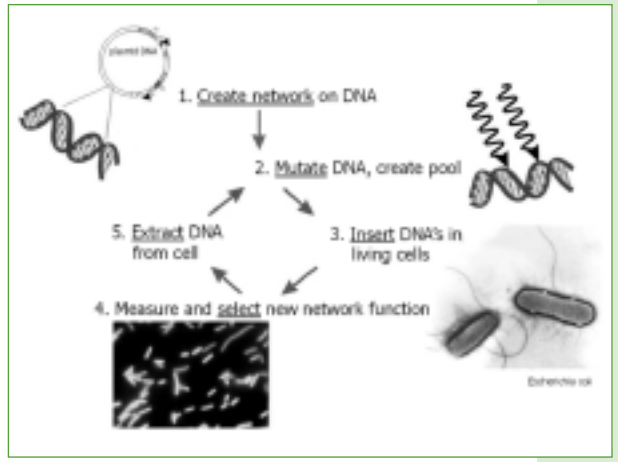


Fig. 1: Evolution procedure of an artificial genetic network, using in vitro mutagenesis and monitioring fluorescence output.

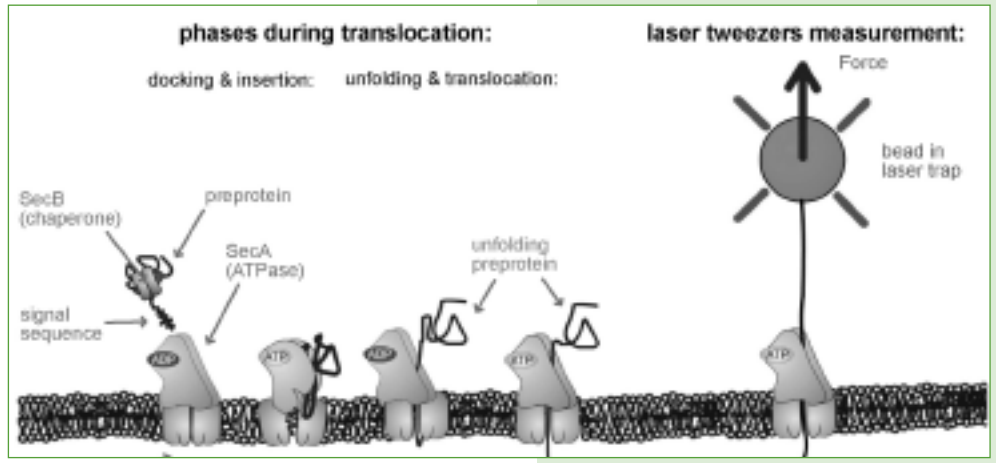


Fig. 2: Overview of the Sec translocation system that exports proteins to the outside of the cell, as found in bacteria such as *E. coli.*

2. RESEARCH

2.3 LIFE PHYSICS THEORY

2.3.1 COMPUTATIONAL PHYSICS
D. Frenkel

Computer simulations allow us to explore the collective behavior of systems consisting of many particles. The research of the Computational Physics group at AMOLF focuses on the study of classical mesoscopic phenomena. This is a scale (nanometers to microns) that is sufficiently small to make a particle-based description of matter essential, yet sufficiently large to make fully atomistic modeling prohibitively expensive. We therefore use (and develop) simplified models that aim to capture the essential mesoscopic physics. Where necessary, we develop the necessary numerical simulation techniques. The focus of our work is on the structure and dynamics of colloidal, polymeric and protein systems.

Part of our numerical work focuses on the study of rare (activated) events, in particular those associated with the formation of crystal nuclei: small crystallites dissolve spontaneously under conditions where big ones are stable. Yet, every crystallite must start small. Macroscopic crystals can therefore only form if, due to spontaneous fluctuations, a crystallite exceeds a critical size. The crystal-nucleation rate depends on P_{crit} the (very small) probability that a critical nucleus forms spontaneously, and on κ, a factor that measures the rate at which critical nuclei grow. In the absence of *a priori* knowledge of either factor, Classical Nucleation Theory is commonly used to predict nucleation rates. This theory offers a simple thermodynamic explanation why small crystal nuclei are less stable (i.e. have a higher free energy) than the supersaturated parent phase. The free energy required to form a crystallite, contains two competing contributions. The first is a negative term that measures the decrease in free energy due to the transfer of particles from the metastable liquid to the solid state. For a crystallite containing N particles, this term is equal to $N\Delta\mu$, where $\Delta\mu=\mu_{solid}-\mu_{liquid}$ is the difference in chemical potential between the solid and the liquid state. The second term is always positive. It accounts for the free energy γA that is needed to create the surface area A of the nucleus. γ is the surface free energy of the solid-liquid interface. Due to the competition between bulk and surface terms, the Gibbs free energy $\Delta G(N)$ required to form an N-particle nucleus goes through a maximum at a value of N^* called the critical nucleus size.

Simulation of crystal nucleation is of interest, because it allows us to study in detail the first, crucial, step in crystallization, namely the formation of the critical nucleus. The "guinea pig" of crystal formation is a suspension of hard spherical particles. This is, arguably, the simplest system that can form a crystalline phase. More importantly, whilst the hard-sphere model was initially introduced as a highly simplified model for simple (atomic) liquids, there now exist experimental realizations of this system, viz. suspensions of hard, uncharged colloids. Our numerical studies allow us, therefore, to compare both with existing theories and with experiments. In particular, we can study the structure of the pathway for crystal nucleation, the structure of the critical nucleus and the rate of crystallization. Our simulations indicate that, at a microscopic level, our understanding of crystal nucleation is far from complete, even for a system as simple as hard spheres. In addition to homogeneous nucleation of hard-sphere colloids, we also study heterogeneous nucleation (i.e. nucleation on an external "seed" surface - see figure), crystallization of charged particles and non-spherical particles (including polymers), and crystal formation in simple models of protein solutions.

In addition, we study the equilibrium phase behavior of novel colloidal systems (with short-ranged or patchy interactions).

Other activities of the Computer Physics group involve the modeling of defects in colloidal crystals, of transport in colloidal suspensions and of activated conformational changes in macro-molecules.

Investigators: S. Auer, G. Boulougouris, A. Caciutto, F. Capuani, I. Coluzza, N. Combe, C. Das, G. Goossen, W.B. Hu, D. Lukatsky, M. Miller, S. Pronk, K. Reuter, T. Schilling and C. Valeriani.
D. Frenkel is also professor of chemistry at the universities of Utrecht and Amsterdam.

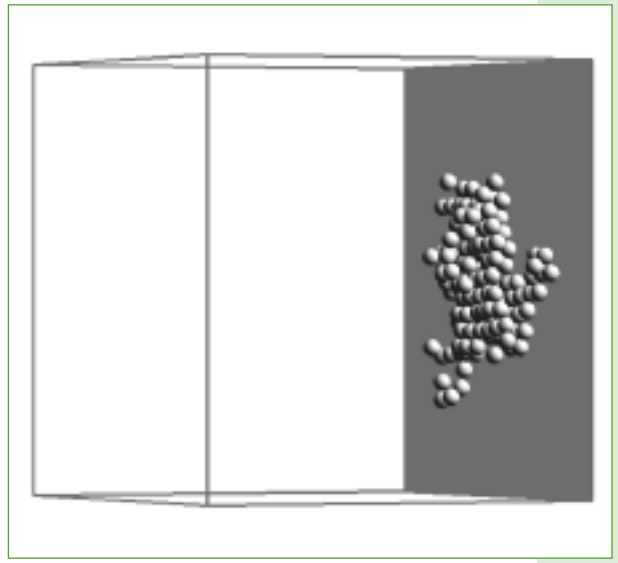


Fig. 1: Numerical study of heterogeneous nucleation. The picture shows a snapshot of a crystal nucleus of hard, spherical colloids on a flat wall. The presence of the wall enhances the rate of nucleation by many orders of magnitude (under the conditions shown in the picture, by a factor 10^{570}). From: S.Auer and D.Frenkel, Phys.Rev.Lett. 91,015703(2003).

2.3.2 THEORY OF BIOMOLECULAR MATTER
B.M. Mulder

The aim of the research in the Theory of Biomolecular Matter group is to understand the individual and collective behaviour of biomacromolecules and their aggregates using the techniques of statistical mechanics and continuum mechanics. The work is inspired by concrete questions regarding the structure and function of actual components of the living cell, with a special focus on plant systems.

Active research topics in the group are:

The mechanism of cellulose biosynthesis in plants
Plant cells are unique in creating an extracellular wall composed of cellulose microfibrils embedded in a multicomponent polymeric matrix. The origin of the highly organized architecture of this fiber-laminate structure is still a matter of intense debate. The primary event in wall formation is deposition of the cellulose microfibrils (CMFs). So far a huge transmembrane protein complex has been identified as the CMF synthase. We are interested in testing the hypothesis that due to the force generated by both polymerization and crystallization of the cellulose these synthases are propelled to move in the plasma membrane of the cell. We approach this problem through explicit mechanistic models of the CMF synthase coupled to phenomenological modeling of cell wall architecture. The work is carried out in close collaboration with the Plant Cell Biology Laboratory of the Wageningen University, headed by Anne Mie Emons.

Dynamics of the plant microtubule cytoskeleton
All eukaryotic cells (higher organisms) posses a cytoskeleton: a highly dynamic collection of filamentous protein assemblies. The cytoskeleton functions as a mechanical "scaffold" for the cell and is involved in the directed transport of materials, the positioning of cellular sub-units, and the generation of forces used e.g. for motility. During the lifecycle of the cell the cytoskeleton is continuously being rearranged. A dramatic example is the sequence of specialized structures plant cells build from microtubules, one of the components of the cytoskeleton. How the cell can bring about these rearrangements is a challenging problem in multi-scale, multi-component physics. One of the interesting aspects of this problem is the presence of active components in the cell, so-called molecular motors, specialized proteins that convert chemical energy into work and motion. Motor proteins are known to act on microtubules and have been shown to be agents of pattern formation in these systems. We are working on construction large-scale, multi-parameter models of active cytoskeletal systems, using both particle based and continuum modeling. In this area we collaborate with the group of Jülicher (MPI-Complex Systems, Dresden) as well as the Plant Cell Biology Laboratory Lab (Wageningen).

Modeling of tip growing cells
Most cells grow by adding material to their surface area in a more or less homogeneous manner. Some cells, however, occurring among algae, fungi, protists and plants are tip-growing: all growth activity is concentrated in a small apical region leading to the formation of long tube-like cells elongating only at one end. This growth mode allows the cells to extend rapidly into the environment and to exert considerable forces. Plant root hairs are an outstanding example of tip growing cells. They serve to anchor the plant root more securely in the soil and act as chemical antennas. In legumes, the plant family encompassing the pulses, the root hairs serve as first contacts for establishing the crucial symbiosis with bacteria in the soil that ultimately causes these plants to be self-fertilizing. The bacteria emit a signaling substance that causes the deflection of the straight growth of the root hair, causing it to curl and create a small hollow in which the bacteria can multiply. Our ultimate aim is to model this process. En route we are studying the geometrical and mechanical aspects of tip growth in general. On this subject we collaborate with Norbert Kern (University of Montpellier).

DNA segregation in *E. coli*
In order to divide, any living cell must not only be able to duplicate its genetic material, but also to spatially distribute it over the two daughter cells. Eukaryotic cells employ a specific molecular "machine" built from microtubules, the so-called mitotic spindle, to perform this task. In bacteria, however, the mechanism of DNA segregation is still a mystery. In *E. coli*, the universal bacterial model system, replication and segregation appear to be a continuous process and no spindle-like machinery has been observed. We are exploring a new model for DNA segregation based on recent experimental evidence for the existence of domains in the bacterial inner membrane, where DNA transcription, mRNA translation and translocation of the resultant proteins occur in co-localized fashion that transiently anchors individual DNA supercoils. The collective action of a number of such 'transertion complexes' provides a symmetry breaking mechanism for the driving apart of the daughter strands of the replicating DNA through directed diffusion. Work in collaboration with Conrad Woldringh (University of Amsterdam).

Investigators: F. Diotallevi, C.C. Tanase and S. H. Tindemans.
B.M. Mulder is also professor in Theoretical Cell Physics at Wageningen University.

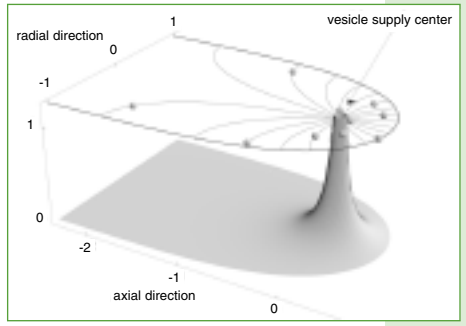


Fig. 1: Density of profile of the exocytotic golgi-vesicles that drive tip-growth in a fungal hypha calculated using the Diffusional Vesicle Supply Center model developed in our group.

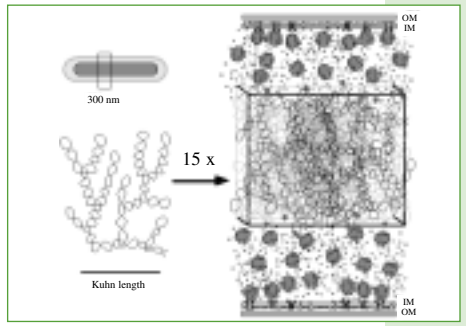


Fig. 2: The organization of the DNA in the *E. coli* bacterium, showing the transient attachment of individual supercoils to the inner membrane at the so-called transertion sites.

2.3.3 BIOCHEMICAL NETWORKS
P.R. ten Wolde

Biochemical networks are the analog computers of life. They allow the living cell to detect, transmit and amplify environmental signals, as well as integrate different signals to recognise patterns in, say, the food supply. The aim of the group Biochemical Networks at AMOLF is to develop and apply new numerical techniques that make it possible to simulate biochemical networks at the molecular level and in both time and space.

Introduction

Biochemical networks can perform a variety of computational tasks analogous to electronic circuits. Yet, their design principles are markedly different. In the living cell, computations are performed by molecules that chemically and physically interact with each other. These components, that constitute the biochemical network, behave stochastically. They often move in an erratic fashion, namely by diffusion, and act upon each other in a stochastic manner – chemical reactions, and equally important, physical interactions are probabilistic in nature. These factors become particularly important when the concentrations of the reactants are low. In the living cell, this is often the case. One would expect, therefore, that biochemical circuits, in contrast to electronic circuits, are highly stochastic and prone to error.

One of the key questions in our research is how biochemical networks can accurately process information in the presence of biochemical noise. In principle, computer simulations are ideal to answer this question. However, the current numerical techniques either ignore the particulate nature of matter, or assume that the living cell is a well-stirred reactor in which the reactants are homogeneously distributed in space. We have recently developed a new technique that makes it possible to simulate biochemical networks at the molecular level and in both time and space. The scheme is highly efficient and allows us to simulate biochemical networks on the relevant biological time scales. Currently, we are applying the technique to study genetic networks and bacterial chemotaxis.

Bacterial Chemotaxis

Bacterial chemotaxis refers to the ability of bacteria, such as *E. coli*, to swim towards higher concentrations of nutrients and away from higher concentrations of various toxic chemicals. The bacterium *E. coli* can do so by operating in only two modes: it can either run (i.e., swim smoothly) or tumble. Tumble events randomize the cell's trajectory, and it is the modulation of their occurrence that allows bacteria to perform chemotaxis. In the absence of any stimulus, the periods of smooth swimming are fairly constant and the bacterium performs a random walk. In the presence of a chemotactic attractant, however, tumbling is partially suppressed whenever the bacterium happens to be swimming in the right direction. The bacterium now performs a biased random walk and it gradually moves in the right direction. The central questions of our research here, are: how reliably are the environmental signals processed? And, what physical constraints does chemotaxis impose upon the design of the chemotactic network? The recently developed numerical technique in our group is ideally suited to answer these questions.

Genetic Networks

In our other line of research, concerning genetic networks, we combine database analyses with computer simulations. Genetic circuits can be very stochastic, because the proteins that regulate gene expression are present in very low concentrations. Recently, we have performed a statistical analysis on the spatial organisation of the gene regulatory network of *E. coli*. We found that genes that regulate each other, tend to lie closer to each other than can be expected for a random network (see Fig. 1). Moreover, these genes tend to be transcribed in divering orientations. This "bioinformatics" study clearly supports the idea that the performance of a genetic circuit can depend on the spatial wiring of its components, but it cannot yet explain why this is so. To this end, we have performed computer simulations on a number of spatial network motifs that were identified by our database analysis. The simulations revealed that 1) a spatial arrangement of operons in which one protein can simultaneously activate two operons can significantly enhance the reponse of the network and 2) a molecular architecture in which the upstream regulatory regions of two operons overlap, can strongly enhance the stability of so-called genetic switches. This shows that even though the discrete nature of molecules makes genetic networks intrinsically stochastic, nature can also exploit the richness of molecular architecture to design stable and sophisticated computing devices. In the future, we intend to investigate the possibilities and limitations of molecular design in more detail using the recently developed numerical technique. In addition, we aim to construct models that allow us to study the spatial evolution of gene regulatory networks.

Investigators: M. Morelli, S. van Albada and R. Allen.
P.R. ten Wolde also has an appointment at the Vrije Universiteit in Amsterdam.

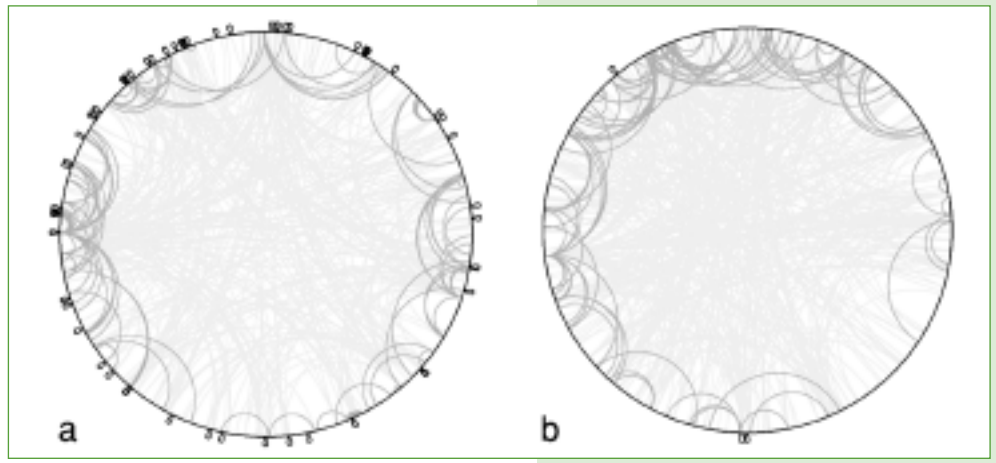


Fig. 1: The gene regualtory network of *E. coli* shown as links between operons on the genome. Maps are shown for (a) the real network of *E. coli* and (b) a representative `randomised' network with the same topology but a random permutation of the identities of the operons. The 'color' code is: dark: distances, s, less than 10 kbp; medium: 10 kbp < s < 500 kbp; light: s > 500 kbp. Note the much greater prevalence of the `short' distances in the *E. coli* map (a) compared to the randomised map (b).

2.3.4 PROTEIN FOLDING
H.G. Muller

The Protein-Folding group performs computer modeling of the structure and dynamics of biological macro-molecules, or systems of such molecules, at various levels of abstraction. The simplest models represent the bio-polymers on a lattice, each monomer occupying a lattice site. Due to their simplicity, these are very useful for studying very slow processes (such as the folding of a single protein into its native shape), or very complex systems (cellular systems, or even complete 'minimal' cells). At the other end of the spectrum of methods, there are Monte-Carlo and molecular-dynamics studies of (fairly small) molecules in atomic detail employing realistic interaction potentials.

Folding of single protein molecules can be studied in a simple model where each amino acid is represented by a single particle that can hop between sites on a cubic lattice. Amino-acid-specific interactions between non-bonded nearest neighbors turn out to be sufficient to allow the design of model poly-peptide chains that fold into a unique native conformation. The folding process in this model system is qualitatively similar to the folding of real-life proteins, and thus can be used as a test-ground for search algorithms aided at structure prediction. In particular, we study the application of genetic algorithms to speed up the search process, where randomly chosen local sub-structures of various previously reached low-energy conformations are combined to generate new trial structures.

Another area of interest is the study of conformational changes in proteins. Many proteins rely for their function on conformational changes, to modulate their catalytic activity, coupling of chemical reactions, or their binding affinity for other macro-molecules. Motor proteins are examples where all these aspects are combined into a machine-like operating cycle that generates mechanical work from chemical energy. We study the strategies that can be used to perform this conversion, by modeling motor proteins at the level of flexibly connected domains. One way to look upon conformational change is as folding into a number of alternative states. We therefore also study the design of proteins with multiple native states in the framework of the simple folding models.

One topic of special interest is the modeling of self-replicating systems. The basis of this research is 'holistic modeling', i.e. employing models in which both chemical-bond formation and physical (Van der Waals-like) interactions are derived from a unifying interaction potential between the model atoms. Such models can not only be used to describe the folding and coalescence of the involved macro-molecules, but also allow modeling of catalysis (by modifying rate-determining transition-state energies by Van-der-Waals interactions with a suitably chosen environment). This in particular opens the possibility to design molecules that (within the framework of the energy rules) perform catalysis of their own synthesis. If we can design a set of molecules that together would catalyze synthesis of every molecule in the set, this would in fact represent a novel type of 'artificial-life'. An even deeper question, once the existence of this type of A-life has been demonstrated, is if such a selfreplicating system can spontaneously arise from self-organization of much simpler molecules.

Investigators: C. Dinu.
H.G. Muller is also professor of physics at the Vrije Universiteit in Amsterdam.

2. RESEARCH

2.4 NANOPHYSICS

2.4.1 OPTO-ELECTRONIC MATERIALS
A. Polman

This group investigates optical phenomena in materials made using nanoscale fabrication technologies. The research program includes the manipulation of light in photonic crystals, optical phenomena in micro-resonators, light emission from silicon nanostructures, and energy transfer in plasmonic structures. The aim is to achieve extreme control over spontaneous emission and the propagation of optical modes in nanophotonic materials.

Photonic crystals and the optical density of states

Photonic crystals are a new class of materials that are built from a regular arrangement of a dielectric material that exhibits strong interaction with light. We have investigated photonic "woodpile" crystals, fabricated at Sandia National Labs (J. Fleming) in which we identified a superstructure that reflects itself in an allowed optical mode inside the photonic bandgap, that is due to zone-folding of the bandstructure. We also observe a large modification of the spontaneous emission from optically active erbium ions inside these photonic crystals, and the effects are described by a model that takes into account changes in the local density of states, internal Bragg scattering in the crystal, and the internal quantum efficiency. More recently, our work focuses on Si inverted opal photonic crystals, made by Si infiltration of silica colloidal crystals made by self-assembly (with A. van Blaaderen, Utrecht Univ., D. Norris, Univ. Minnesota). These crystals possess a full photonic bandgap, and are thick enough to obtain complete inhibition of spontaneous emission of an optical probe that is placed inside. We also study the relation between Förster energy transfer and the local optical density of states in highly doped optical materials.

Lasing in active micro-resonators

Optical resonators are geometries in which optical energy can be stored in small volumes at high intensity. Together with the group of K. Vahala (CALTECH), we investigate the doping of toroidal silica micro-resonators with Er ions. In these toroids, light orbits near the surface, and the long confinement time (quality factor $Q>10^7$) effectively wraps a long interaction length into a very small volume. Taking advantage of these effects we have fabricated the world's smallest Er laser with a gain threshold of only a few μW.

Plasmonics

Surface plasmons are electromagnetic excitations that propagate along a metal-dielectric interface, or along chains of metallic nanoparticles. Our goal is to study the generation and manipulation of surface plasmons, with the aim to achieve nanoscale control over the propagation of electromagnetic energy. Surface plasmons and photons do not couple efficiently due to their different dispersion relations. This mismatch can be overcome by using micro-structuring or near-field coupling techniques. We have demonstrated the first generation of infrared surface plasmon polaritons on a silver grating that are generated by optically excited Er ions. We have also developed a highly dispersive silica glass doped with Ag nanocrystals, that shows a strong surface plasmon optical resonance. After MeV ion irradiation of this glass, nanoscale plasmon wires form, that have highly anisotropic optical response due to the strong transverse and longitudinal plasmon coupling. The combination of strong interaction with light and non-linear effects in these materials has lead to the design of an optical transistor that is presently being explored.

Silicon microphotonics

Bulk silicon is a semiconductor with an indirect electronic bandgap and is thus an inefficient light emitter. We fabricate and study Si nanocrystals, in which quantum confinement effects cause an enhanced optical emission efficiency. Using nanoscale engineering and near-field and confocal optical microscopy we study the optical properties of individual and coupled quantum dots (with H.A. Atwater, CALTECH). These Si quantum dots can also act as sensitizers for optically active rare earth ions such as erbium and terbium. We study the coupling between excitonic states in the semiconductor and the electronic states of the rare earths. We have developed a model that predicts how these nanostructures could be used to fabricate a Si-based rare-earth laser or amplifier. In an effort to obtain efficient light emission from bulk Si, we have developed an electrically addressable self-assembled Er-Si-O superlattice that shows bright room temperature photoluminescence from Er at 1.5 μm. It solves nearly all major problems encountered with Er doping of bulk Si so far.

Ion-solid interactions

Ion beams are indispensable tools to dope materials with optically active ions. Ion irradiation can also lead to nanoscale changes in the structure and shape of materials such as colloids, Si nanostructures and lithographic masks. The thermal spike that is generated along the ion track leads to anisotropic deformation, with the material expanding perpendicular to the ion beam. We have developed the concept of a "stress map", that can be used to predict the dynamic stress evolution during ion irradiation at arbitrary irradiation condition. Continuum modeling is used to determine the fundamental mechanisms behind these ion-solid interactions.

Integrated optics and knowledge transfer

Integrated optics is a technology that combines several optical functions on a single substrate. Many of the subjects that we are working on lead to novel components in such integrated circuits. In the past few years, we have demonstrated a miniature optical amplifier, an infrared polymer LED, an erbium-doped Si LED and photodetector, and most recently, the world's smallest erbium laser. We have interaction with several industrial partners worldwide to transfer knowledge acquired from our research program and we regularly file joint patents with industry.

Investigators: T. van Dillen, J. Kalkman, J. Penninkhof, J. Kalkman, A. Tchebotareva, J. van der Elsken and H. Mertens.
Technical support: J. Derks.
A. Polman is also professor of Materials Science at the University of Utrecht.

Fig. 1

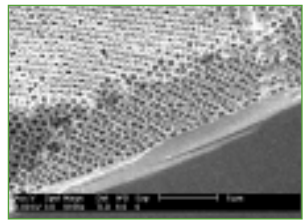


Fig. 2

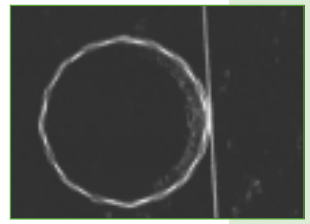


Fig. 1: Erbium-doped photonic bandgap crystal

Fig. 2: Optical modes in an erbium-doped micro-resonator

2.4.2 NANOFABRICATION
J. Verhoeven

This group is involved in two topics:
a) The formation of periodic nanostructures and the interaction of light with these stuctures;
b) Development of a bright x-ray source in a wavelength region from 2-4.4 nm (Water Window). The source is based on Cherenkov radiation.

a) Nanostructures

Introduction

Manipulating light of different wavelengths by interaction with nano-structured systems is a challenging subject in physics and its applications. Multilayered systems at a nano-scale have been produced to reflect radiation in the wavelength region from 1 to 40 nm. AMOLF has been very successful in optimizing the reflectivity by producing smooth interfaces. This was achieved by interaction with low energy ions. A new project concerns the interaction of light in the visible region with metal particles of nano-scale dimensions. The formation of periodic arrays of nanodots forms a major part of this project.

Multilayers

The optical performance of a multilayer system depends on contrast at the interfaces and interface roughness related to the wavelength. Impact of energetic ions after deposition of one of the components or during deposition has demonstrated to be beneficial in reducing the surface roughness of the layer. A major problem has been caused by interaction of energetic ions and the interface underneath. Intermixing will occur and can result in a well-defined compound layer (Mo/Si) or a graded density layer (W/Si). The prevention of intermixing forms a major part of our investigations.
As reflection is based on interference, these multilayers can also be applied as dispersive elements. In that case reflectivity as well as wavelength resolution are to be optimized. For resolution the number of interfaces that contribute to the reflection is decisive. A computer program was written for optimization.
These experiments are done in part in collaboration with the Laser Plasma X-ray group of Dr. F. Bijkerk at the FOM Institute for Plasma Physics, Rijnhuizen.

Nanodots

Light interacts with metallic particles by excitation of plasmons. The effect of interaction with many particles has been investigated extensively during the past century. The interaction with individual particles and coupling of plasmons of one particle to the other is a new field of research.
From earlier work on the formation and stability of palladium particles on a TiO_2 (110) surface we learned that defect sites on a surface act as trapping sites for nucleation. Step edges at the surface form a clear example (figure). However, local reduction of the surface has demonstrated to be another possibility to form a trapping site. Our investigations aim to generate trapping sites by application of local reduction of the surface of a thin SiO_2 overlayer using electron stimulated desorption. We will study nucleation of different metals (Ag, Au, Pt etc.) at those trapping sites after deposition and after subsequent heating. The investigation includes the nucleation mechanism and the influence of a chemical reactive environment, the relation between the size of the trapping site and the size of the particle and the stability of the particle. The ultimate goal is one or two-dimensional periodic structures of nuclei of similar size that will be used for optical experiments.
A part of these experiments is done in collaboration with prof. B. Nieuwenhuis, Leiden Institute of Chemistry of the Leiden University.

b) X-ray source in the water window (2-4.4 nm)

Introduction

The advantage of the application of x-rays in the wavelength region from 2-4.4 nm in biological microscopy is an enhanced contrast due to a high absorption of carbon. A source with a high brightness and a small bandwidth is required. Synchrotrons have been available as a major source for radiation with the required wavelength. As an alternative a laser plasma source has been applied. We proposed a source based on Cherenkov radiation.

Cherenkov radiation

When charged particles pass a medium with a velocity higher than the phase velocity of light for a certain wavelength, light of that wavelength will be generated. This requirement means in practice that the real part of the refractive index n should exceed 1. In the x-ray region this occurs only around absorption edges of some elements. For wavelengths below 2 nm no edges for which n sufficiently exceeds 1 can be found. Good candidates for radiation in the "water window" are the L edges from V(2.42 nm) and Ti (2.73 nm). We used 10 MeV electrons to demonstrate the phenomenon. Our experiments revealed a yield of 3.5×10^{-4} photons/el for Ti and 3.3×10^{-4} photons/el for V. All Cherenkov radiation is generated within a small cone from 5 to 12° around the path of the charged particle. Compared with characteristic radiation, the whole yield is available for application provided the proper optics is used. A new challenge will be to combine a Cherenkov source with reflective (multilayers) and/or zone plate based optics for imaging purposes.
This project is a collaboration with the group of prof. dr. M.J. van der Wiel, Accellerator Laboratory, University of Eindhoven.

Investigators: M.L. Alink, R. Tsybukh, M. Kessels, S. Dobrovolsky, W. Knulst and J. Luiten.
Technical support: C. Rétif and H. Zeijlemaker.

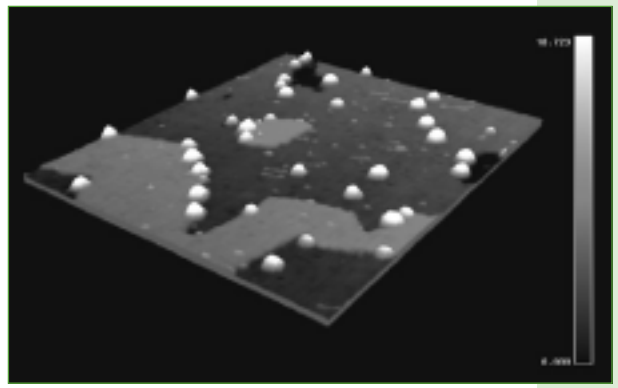


Fig. 1: An example of step edge decoration by Pd clusters on a TiO_2 (110) surface

2.4.3 PHOTONIC MATERIALS THEORY
A. Tip

A central issue in this group is the study of Maxwell's equations for macroscopic dielectrics, in particular periodic structures such as photonic crystals. Main topics under consideration are the band structure and Green's functions for absorptive photonic crystals and the transport of excitation energy between atoms embedded in dielectrics.

Band structure of photonic crystals

Photonic crystals (PC) possessing bandgaps are important devices in view of technological applications. In a complete gap no field modes are present and in partial (or stop) gaps field propagation in one or two directions is inhibited. Thus, in the radio frequency range, in particular at microwave frequencies, bandgap photonic crystals (BPC) can be used to improve the performance of antennas. At optical frequencies embedded atoms will not decay if the transition frequency falls into a gap, since there are no field modes available to carry away the energy and this can be useful in devices such as solar cells and solid state lasers. The subject is studied experimentally in our department.

An interesting aspect of photonic crystals is that, given the dielectric properties of the materials used, the band structure can be predicted numerically, giving useful guidelines for the actual manufacturing of PC's. Thus we have made extensive calculations, using an adaptation of the KKR-method of solid state physics. That method is tailor-made for the electromagnetic situation (typically nonoverlapping spheres on lattice sites). We found that a large contrast in the permittivity ε between scatterer and background is required to obtain appreciable bandgaps in the optical regime. Here available materials set severe restrictions.

The situation improves significantly for Drude-type metallic spheres. They behave as lossy dielectrics with the real part *Re* $\varepsilon(\omega)$ of $\varepsilon(\omega)$ (ω is the angular frequency) ranging through a large interval, including negative values, as ω runs through the optical frequency range. For 3D structures, disregarding absorption, a large bandgap is found at frequencies where the absorption is small, thus *a posteriori* justifying its neglect. This work is continued by van der Lem, who studied 2D configurations (periodic arrays of parallel cylinders).

Another class with favorable bandgap properties are woodpile photonic crystals, crossed layers of square rods with periodic spacings. This avenue is explored by B. Gralak, a postdoc from France, a specialist on this matter. Here the KKR approach is less suitable and Gralak has set up a different approach. Work together with M. de Dood, who was experimenting on woodpile systems, showed that Gralak's numerical results come close to measured reflection data.

In the mean time, in collaboration with J.M. Combes (Toulon, France), we investigated the general properties of band structure in the presence of absorption. It was found that the bands, originally intervals on the real axis, change into islands in the lower complex plane. Also bandgaps no longer exist in frequency regions with non-zero absorption. This can be understood by realizing that gaps arise due to the coherent scattering from scatterers at all distances. But, if absorption is present the fields will be attenuated appreciably when arriving at or originating from distant scatterers, thus changing the situation. Nevertheless one expects a decrease in atomic decay constants at frequencies where a gap would be present without absorption.

The band structure properties were recently confirmed numerically by van der Lem and Gralak for the cases of 2D-cylinders and square rods, respectively. Their real parts do not differ much from the absorptionless situation and the imaginary parts remain quite small. This suggests the possibility of using perturbation theory with the aborptionless case as zero order. This is under investigation in a joint effort with J.M. Combes. At present we are also engaged in determining numerically the Green's function for the appropriate Helmholtz equation, atomic decay constants being proportional to its imaginary part.

Migration of atomic excitation energy through dielectrics

In a number of technological applications it is useful or even necessary to modify the radiative decay properties of atoms, in particular to suppress such a decay. In principle this can be done by embedding the atom in a photonic crystal with a bandgap in the frequency range of interest, although actual realizations are still to be obtained. In practice many embedded atoms will be present and an excited atom can not only deexcite by direct photon emission (if not forbidden by the presence of a bandgap) but it can also transfer its energy to other atoms, for instance by photon pickup by another atom or by Foerster type processes. In order to disentangle the different occurring processes, it is important to have a theoretical description available. Since photonic processes in the presence of dielectrics are a relatively new area, much remains to be done. We recently started an investigation of the situation, maintaining close contacts with the Jena group (D.G. Welsch and L. Knoell), which is also investigating these issues.

An important matter, about which conflicting results can be found in the literature, is the effect of band gaps on Foerster processes. We found that this is mainly a matter of definition, involving the gauge that is used. A generalized Coulomb gauge gives a splitting into radiative and non-radiative interactions, where the second are determined by potentials given by the Poisson equation with the static permittivity $\varepsilon_{stat}(x)$. Within this set-up band gaps in the radiative spectrum have nothing to do with Foerster processes.

Investigators: H. van der Lem and B. Gralak.

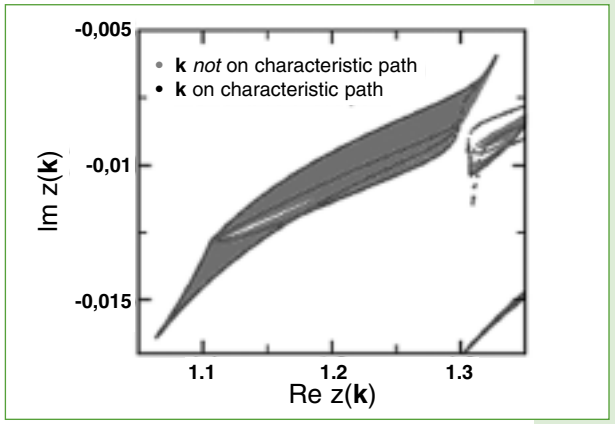


Fig. 1: Detail of the band structure in the complex plane. Note the small hole in the swordfish shaped object.

2.4.4 ORDER/DISORDER IN SOFT MATERIALS
W.H. de Jeu

The objective of the group is to study and control the ordering of soft materials, especially (but not only) at surfaces. We use in-house x-ray reflectivity and optical and atomic force microscopy, complemented by grazing-incidence x-ray diffraction at synchrotrons, to study nanostructures in block copolymer films and polymer crystallisation in confined geometries. We apply small- and wide-angle x-ray scattering (SAXS/WAXS) to investigate ordering and crystallisation of polymers under shear. Finally smectic membranes are studied as model systems of low-dimensional ordering, especially with respect to the dynamics of the fluctuations.

Ordering and crystallization in polymers
Time-dependent SAXS measurements indicate that in the melt of isotactic polypropylene a weak shear field induces smectic ordering at temperatures well above the melting point of any crystalline phase (figure 1). The existence of such a smectic phase in a flexible-chain polymer supports the idea of induced rigidity, which takes in iPP the form of a 3/1 helical structure. The smectic periodicity of about 4 nm comprises a rigid helical sequence of at least 11 monomers and a short random-coil part of about 1.4 nm, which assemble into a fibrillar morphology. The smectic ordering is also highly relevant for the debate about pre-ordering before polymer crystallization at lower temperatures.

Crystallisation in diblock co-polymer films
In a diblock copolymer ordering arises due to the difference in chemical properties of the A- and B-blocks ('surfactant'-like behaviour). For about equal amounts of A and B the resulting microphase separation leads to a lamellar structure. In thin films, the randomly oriented microdomains become macroscopic lamellae under the influence of the surfaces. Films of such symmetric diblocks (for example PEO-PB_h) are suitable model systems to study the isothermal crystallization of the semi-crystalline PEO-block in the confined surroundings of the amorphous PB_h block. For an asymmetric situation the micro-phase separation prefers a hexagonal structure of PEO cylinders in a matrix of PB_h. Now coupling and competition arises between the (hexagonal) block ordering and the (lamellar) crystallisation of the PEO block. In this situation crystalline lamellae oriented perpendicular to the substrate have been observed. We postulate a model in which an order-order transition from a cylindrical to a lamellar morphology takes place upon crystallization.

Nanostructures in fluorinated alkanes (EU-Network POLYNANO)
Semi-fluorinated alkanes of the general structure F-$(CF_2)_m$-$(CH_2)_n$-H (in short F_mH_n) self-organize in a wide number of different smectic and crystalline phases due to the incompatibility between the fluorinated and the alkyl part. Figure 2a shows the reflected x-ray intensity of monolayers of $F_{14}H_{20}$ on silicon prepared at Ulm University from a low-concentration solution. The interference fringes indicate a total film thickness of 3.7 nm; a simple two-layer model can fit the full data. The difference between the Van der Waals diameter of the fluorinated and hydrogenated parts leads to a tilted arrangement. Assuming a close-packed organization of the molecules this gives a tilt angle α=143°. Adding the vertical projection of the hydrocarbon block length (2.04 nm) to the length of the fluorinated part (1.64 nm) gives 3.68 nm, in excellent agreement with the thickness as determined from the x-rays (figure 2b). However, this optimum packing can only materialize in one direction, leading to various types of ribbon-like structures.

Smectic membranes in motion
The reduced dimensionality of smectic liquid crystals leads to strong thermal fluctuations of the layers. As a consequence their positional ordering is not truly long-range: the mean-square displacement of the layers diverges with the sample size (Landau-Peierls instability). Smectic liquid crystals can be suspended over an opening in a solid frame. These smectic membranes have a controlled thickness while the layers order uniformly parallel to the surfaces. To study their dynamics x-ray photon correlation spectroscopy using coherent x-rays at ESRF (Grenoble) has been combined with neutron spin echo measurements at ILL (Grenoble). This allows measuring a new area of relaxation times in the range from 10 ns to 10 μs. Fluctuations of a specific wavelength can be probed at off-specular scattering positions. The x-ray experiments indicate a crossover from oscillatory damping at long wavelengths to exponential decay for shorter ones. This region of relatively slow relaxation times is dominated by the surface tension: the membrane behaves simply as a fluid film. The neutron results allow reaching larger off-specular positions. This region is determined by typical liquid-crystalline bulk elasticity, and the relaxation times decrease with the wave vector.

Investigators: M. Al-Hussein, D. Lambreva, L. Li, . Mouresan, B.I. Ostrovskii (guest), and I. Sikharulidze.
Technical support: E. Prins.

W.H. de Jeu is also professor of Physical characterisation of polymers at the Eindhoven University of Technology.

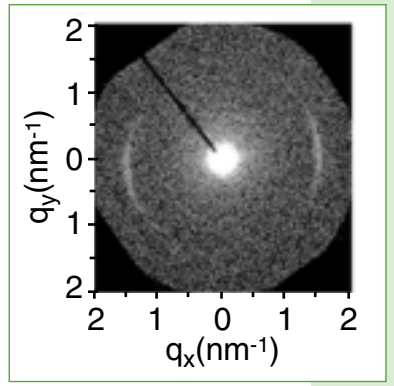


Fig. 1: Two-dimensional SAXS pattern of iPP displaying shear-induced smectic ordering at 180 °C after a steady shear with a shear rate of 1 s^{-1} for 2 min.

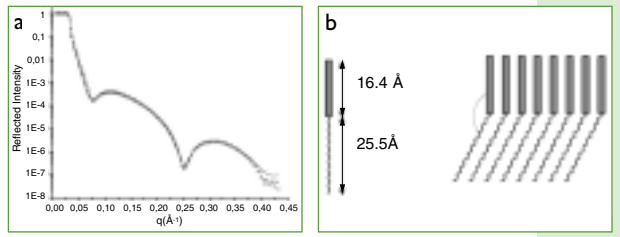


Fig. 2: Monolayers of a semi-fluorinated alkane. (a) Experimental x-ray reflectivity data (circles) with fit (full line). (b) Sketch of the molecular organization.

2.4.5 NANOPHOTONICS
L. Kuipers

The NanoPhotonics Group was started March 2003 with the central aim of manipulating and investigating light at the nanoscale. The goal is to explore the natural frontiers of light control: length scales of a single wavelength or below, and time scales approaching that of an optical cycle, i.e., fs. Central to the approach of the group is that the optical manipulation at the nanoscale is also investigated at that scale.

Photonic structures

The light manipulation is based on concepts derived from solid state physics. One of the most powerful novel materials in recent years for nanophotonics has been that of photonic crystals. Photonic crystals are composites of different periodically varied dielectrics. Under the proper conditions a gap opens up in the photonic dispersion relation (similar to the band gap for electrons in an atomic lattice). Optical frequencies located inside the gap are forbidden in the crystal. Tailored local defects in a perfect crystal may result in optical states in the gap. Point defects thus act as high-Q resonators, whereas line defects guide light of the allowed optical state through the crystal.

Nanostructured metals also provide a potent route for nanoscale light manipulation. A beautiful example was recently achieved in arrays of sub-wavelength air holes in optically thick metal films. Normally, subwavelength holes will only transmit a minute fraction of the incoming light. However, these periodically ordered films exhibit an extraordinary transmission phenomenon: for certain colours the transmitted fraction of incident light exceeds the open fraction of the film. The enhanced transmission has been attributed to a collective resonant excitation of surface plasmon set up by the hole array. Recently, we have shown that the extraordinary transmission phenomenon can actually be influenced by the *shape* of the holes on the nanometer scale. The transmission maxima could be increased by almost an order of magnitude and red-shifted by more than 100 nm. Both observations, which are not explained by existing theories, highlight the potential to manipulate light by truly controlling the geometry of materials on the nanometer scale. At present, it is unknown how the surface plasmons and resonances, due to the hole shape, co-operate to enhance the transmission of the film.

Tracking light at the nanoscale

In order to control light at the nanoscale, a large interaction of the light field with the nanoscale geometry is crucial. Small variations in geometry will have large consequences that are, at present, not easily predicted with theory. It is therefore imperative to investigate the optical properties and the topography of the structures at the nanoscale itself, so that the influence of geometry on the light flow can be directly unravelled. Central in these studies is a new near-field optical microscope. This instrument is not only phase-sensitive but it can also track fs laser pulses in space and time as they propagate through a nanostructure. The new microscope will be able to work both in collection and illumination mode so that transmission phenomena also become accessible. It will be able to measure local variations in refractive index. Moreover, it can separately measure the phase velocity and the group velocity. In addition it is able to visualize scattering processes at the nanoscale. The nanoscale measurements will be used to test existing theoretical models and point the way to new models.

A budding new group

In April 2003 M. Sandtke, who did his undergraduate work in the group of Prof. D. Lohse, joined the group as a PhD student. He is currently setting up ultrafast experiments on nanostructured metal films. Together with H. Schoenmaker and I. Cerjak and in collaboration with the Applied Optics Group at the University of Twente, we are finalizing the design of the new near-field optical microscope.

Investigators: M. Sandtke.
Technical support: H. Schoenmaker.
L. Kuipers is also professor at the University of Twente and program director of the MESA+ Research Institute (Twente).

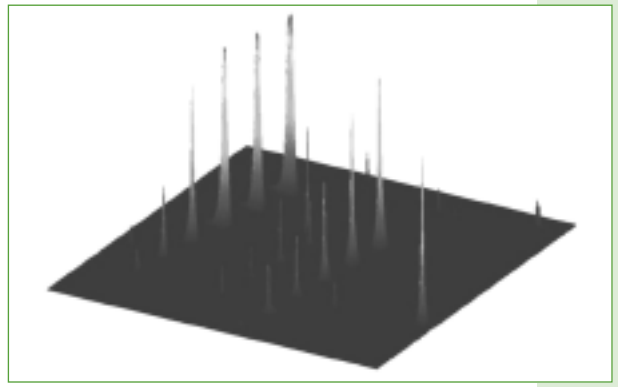


Fig. 1: A far-field optical image (image size 2000 μm^2) of transmission through a number of different periodic air hole arrays in a 200 nm thick gold film. Each peak indicates light transmission through a single array. Every array contains holes that are either different in shape or in size. The variations in peak intensity clearly highlight the effect of hole size and/or nanoscale shape.

2. RESEARCH

2.5 EXPLORATIVE RESEARCH

2.5.1 MOLECULAR PAINTINGS RESEARCH
J.J. Boon

Easel paintings, an important part of our cultural heritage, undergo undesirable physical and chemical changes that affect their aesthetic quality and threaten their keeping. The Paintings Studies Group is undertaking fundamental research into the molecular aspects of aging in paintings with a special focus on the reactions between organic and inorganic fractions of the paints.

The Paintings Studies group at AMOLF is building on the expertise obtained during MOLART, the NWO Priority program on Molecular aspects of Aging in Art and participates in various collaborative studies with art institutions in the Netherlands and abroad. There is an open laboratory agreement with the Royal Cabinet of paintings De Mauritshuis and the Vincent van Gogh museum.
Dr. A. Burnstock from the Courtauld Institute of Art in London received the Joop Los fellowship to facilitate her paintings studies at AMOLF. Our present research is supported by the FOM program 49 and projects in the new NWO De Mayerne Program on: Historically accurate reconstructions of paintings [P.I. Carlyle; ICN and AMOLF], Coordination chemical studies of lead in traditional oil paint [P.I. Haasnoot; University of Leiden], The media by Van Gogh [P.I. Hendriks; Van Gogh Museum], Paintings of the Oranjezaal [P.I. Van Grevenstein; SRAL] and Imaging studies of paint cross sections [P.I. Boon; AMOLF]. New collaborative projects funded in 2003 are "The identifiction of underdrawing materials" [P.I. Prof. M. Faries; University of Groningen] and "Changes in opacity of 19th C paints" [P.I. Dr. K.J. van den Berg; ICN].

Oranjezaal project
MOLART's multidisciplinary project on the varnishes, binding media and pigments of the paintings ensemble in the "Oranjezaal" of the Royal Palace "Huis ten Bosch" in the Hague is continued in the De Mayerne program by L. Speleers, A. van Loon, Ester Ferreira, M.Clarke and M. van Eikema-Hommes. The ensemble consists of large-scale canvas and panel paintings glorifying Stadholder Frederik Hendrik that were made by famous 17th Century artists from the Northern and Southern Netherlands. Systematic studies are performed on pigments and media to understand the relationship between the choice of the paintings materials and the artistic intentions. Some paint defects are being studied in more detail, i.e. whitening of bone black paint, vermillion disease, smalt discoloration and protrusion formation in lead containing paint.

Imaging studies of paint cross sections
The De Mayerne MOLMAP project at AMOLF aims at optimisation of the extraction of information on the spatial distribution of binding media and pigments in tiny embedded paint chips. Data from imaging techniques like SIMS, microscopy FTIR, Reflection Visible Spectroscopy, and SEM-EDX are compared and superimposed. The additional value of new viewing techniques such as imaging Raman spectroscopy and imaging electron backscattering diffraction (EBSD) are being explored. A special focus is on imaging SIMS of paint cross sections carried out by K. Keune. The project by B. Marino is aimed at the comparative study and analysis of particle distributions in paint layers of Van Gogh and others.

Extruding and protruding metal soap aggregates
The transition of the initial oil derived cross-linked elastomeric structure to the metal coordinated ionomeric structure of aged paints causes problems in many paintings. Aggregation of metal soaps is taking place in over a hundred paintings ranging in age from the 16th to 20th century. A joint project with E. Gore and A. Burnstock of the Courtauld Institute demonstrated in 2002 that soap formation is a common process that takes place in most paintings. In some paintings however the dispersed metal soap phase-separate into lumps. Zinc soaps forming in yellow leadsulfochromate paint in Falling leaves: Les Alyscamps (F486) by van Gogh, have massively aggregated and are now actively extruding through the varnish layer. Early stages of the formation of metal soap aggregates recognised in the Rembrandt painting "The Anatomy lesson of Dr. Nicolaes Tulp" in the collection of the Mauritshuis have allowed the development of a dynamic model. Projects to understand the mechanism and driving forces of protrusion formation are underway. The questionnaire on metal soap aggregation [P. Noble; Mauritshuis] can be downloaded to document the phenomenon in museum collections.

Organic chemistry of paintings
Direct mass spectrometric techniques (DTMS and (MA)LDIMS) are applied to homogenized samples and extracts with a special focus on the identification of binding media components, organic dyes and lake pigments, waxes, varnishes and resins in traditional and modern paintings. The project by O. Katsibiri is focused on the identification of varnish layers and mordants on post-Byzantine icons. Collaborative studies are undertaken to study the effect of aqueous and non-aqueous cleaning methods on paintings.

Molecular archaeology
Our group supports a small amount of DTMS work on archaeological materials: carbonaceous residues on archaeological pottery (T. Oudemans) and charred residues from peas and wheat (F. Braabaart).

Investigators: F. Braabaart, A. Burnstock, L. Carlyle, M.Clarke, E. Ferreira, F. Hoogland, O. Katsibiri, K. Keune, G. Languri, B. Marino, P.Noble, T. Oudemans, L. Speleers.
Technical support: J. van der Horst, M.C. Duursma and A. van Loon.
J.J. Boon is also professor of analytical mass spectrometry at the University of Amsterdam.

2.5.2 ANTIHYDROGEN
L.D. Noordam

Thousands of antihydrogen atoms, the antimatter counter part of atomic hydrogen, have been produced in cold plasma's in 2002 at CERN. Future experiments aim to trap antihydrogen atoms such that laser spectroscopy will provide stringent Charge-Parity-Time reversal tests. It may even be possible to directly observe the gravitational force on antimatter atoms. Experiments on matter at AMOLF aim to explore new directions in recombining the anti particles into antihydrogen Rydberg atoms and mechanisms for de-excitation of the positron to the ground state.

Recent experiments by the ATHENA and ATRAP collaboration at CERN show that in a cold plasma of antiprotons and positrons in a magnetic trap, the antihydrogen atoms (see figure 1) are formed in high Rydberg states. From the long list of steps that need to be taken to test antimatter properties we focus on two steps: (1) the recombination of the antiproton and the positron to form antihydrogen atoms, often in a high Rydberg state and (2) de-excitation from these Rydberg states towards the electronic ground state.

Recombination

Making an (anti) atom is not easy. Several groups are investigating the most suitable recombination process to release the excess energy of the positron in order to recombine the antiproton-positron pair. For instance, a third positron can pick up the energy released (three-body recombination). Alternatively, the antiproton-positron pair can emit a photon (radiative recombination). In the presence of a strong magnetic field the rates of the above processes are experimentally and theoretically unknown. At AMOLF we investigate new avenues to obtain efficient recombination. For instance, we have developed a new technique of fast switching electric fields to catch the free positron flying by an antiproton (Phys. Rev. Lett. 84, 3799 (2000)).

De-excitation

Although the antihydrogen production in 2002 is a major achievement, the produced atoms are in a Rydberg state and hence not yet suitable for ground-state spectroscopy. Several de-excitation schemes are discussed such as far-infrared laser de-excitation and collisional de-excitation, or just wait until the positron has decayed. Little is known about the best de-excitation strategy for Rydberg atoms in magnetic fields. Given the limited knowledge on Rydberg-Rydberg transitions in a strong magnetic field, there are currently no estimates on how the de-excitation process evolves in the plasma and how the production of low-lying states can be enhanced.

Future experiments

Test experiments at AMOLF will, for practical purposes, be performed with matter particles, rather than antimatter. We select research topics such that we can study new and appealing physical phenomena that might be relevant for the antihydrogen research. Visits to CERN in 2004, 2006 and beyond, to implement new findings, are certainly possible. The research at AMOLF focuses on two challenges of the anti-hydrogen research program (see e.g. Physics Today January 2003):

What is the recombination mechanism of cold plasma's in a strong magnetic field that result in the formation of atoms in a highly excited state? Our efforts will be both experimental and theoretical. In the experiments we focus on the impact of RF radiation as induced by the cold plasma on the Rydberg atom recombination and ionization.
How can we drive the Rydberg population to the ground state? To find an optimal source for laser-stimulated de-excitation we will measure the Rydberg-Rydberg transitions in the presence of a strong magnetic field. To investigate stimulated de-excitation with lasers we have access to the Dutch free-electron laser facility FELIX with a tuning range from 4 to 250 μm. Moreover dipole transitions (as measured in such spectra) also play an important role in collisional processes. We aim to use the spectra as input for collisional de-excitation models.

In short, we foresee that experimental explorations with normal matter will open new avenues in the production of the antimatter counterpart of hydrogen, antihydrogen.

The experimental group at AMOLF has a long-standing theoretical collaboration with the group of prof.dr. F. Robicheaux (USA).

L. D. Noordam is also professor of physics and chemistry at the Vrije Universiteit Amsterdam.

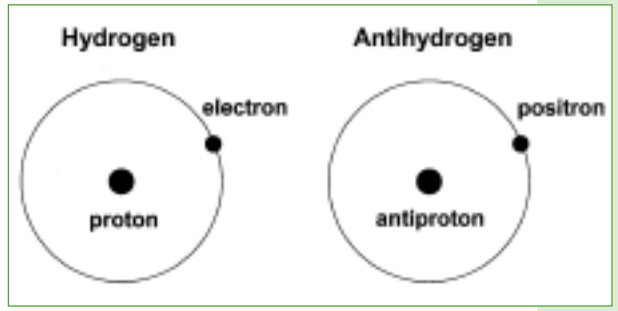


Fig. 1: Antihydrogen is the antimatter counterpart of hydrogen

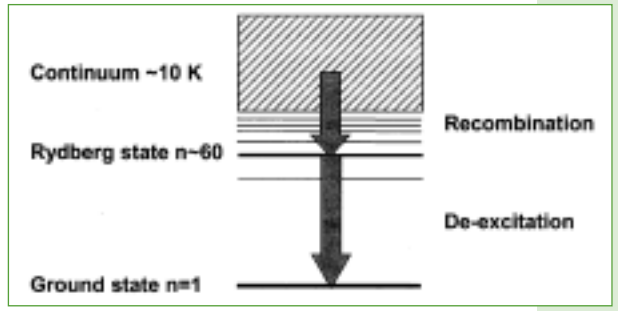


Fig. 2: The formation of antihydrogen in the ground state is foreseen to be a two-step process: First the cold positron recombines with the antiproton to a Rydberg state. Next by de-excitation the formed Rydberg state relaxes to the ground state.

3. SUPPORT

3.1 Amsterdam *nano*Center: soft-bio-nano-facility

General description

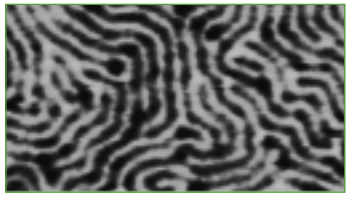
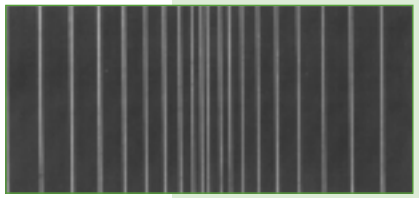
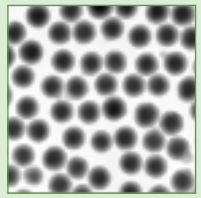
The Amsterdam *nano*Center is a facility for nanofabrication and nanocharacterization using a combination of techniques. It includes a cleanroom with facilities for optical- and electron beam lithography and plasma etching, a facility for thin film deposition, a biophyiscs/chemistry laboratory, and innovative optical tools for nanofabrication, manipulation and analysis that include optical tweezers, confocal microscopy, and near-field optical microscopy.
The Amsterdam *nano*Center has been founded on the initiative of groups from AMOLF, the University of Amsterdam and the Free University. It is part of the FOM Institute for Atomic and Molecular Physics (AMOLF) in Amsterdam, and serves research groups from the three Amsterdam participants. It is also available for users from outside Amsterdam. Several existing facilities at AMOLF are included in the *nano*Center, and have thus become available for outside users as well.

Equipment

A clean room, total area 57 m^2, houses an electron beam pattern generator, resist processing equipment, a reactive ion etching system and an inspection microscope. All instruments with less stringent cleanliness requirements are housed outside the clean room. These include fabrications tools, inspection instruments and nanoscale research tools. The fabrication tools include optical lithography, rapid thermal annealing, a tube furnace, thin film deposition facilities and an optical tweezer set-up for generating tailor-made colloidal masks. The inspection tools include a high resolution scanning electron microscope equipped with EDX, Rutherford backscattering spectrometry, spectroscopic ellipsometry, AFM, variable-temperature STM, AES, XPS, LEED, MFM, MOKE, SQUID magnetometry and X-ray diffractometry. The nanoscale research equipment includes the optical tweezer, all scanning probe microscopes including a combined NSOM/confocal/AFM instrument that is able to measure spatially resolved three-dimensional Raman spectra.

Facility

The Amsterdam *nano*Center is a facility open to researchers of nanotechnology also from outside Amsterdam. The researchers will be responsible for their own fabrication and measurements. To start their use of the facility they will contact L. Kuipers to establish their requirements. Subsequently, they will be instructed in the use of the relevant instruments. J. Verhoeven is responsible for the daily operations of the *nano*Center.

Figures: (left) Magnetic force microscopy image of 100 nm wide stripe domains in GdFe thin films (courtesy of dr. J.B. Goedkoop). (middle) Pattern of fluorescently labeled proteins produced with microcontact printing. (right) Core-shell colloids that will be used to manipulate light on the nanoscale.

3.2 ELECTRONICS AND INFORMATICS DEPARTMENT

The main task of the Electronics and Informatics (E&I) department at AMOLF lies in designing, building, maintaining and supporting the electronic components, and increasingly also the controlling software, of the experimental set-ups in the lab. This requires a variety of skills, ranging from computerized print board design to software engineering in C++ or high-level tools like LabView. The department has to cope with a mixture of high-urgency, short-term jobs, as well as complex long-term projects. In order to meet this challenge, the department has recently adopted a new procedure to streamline workflow, providing the "customers" from the scientific groups with more insight into the progress of their projects.

E&I is also responsible for the computer infrastructure of AMOLF. This involves supporting a large number of PC's, workstations and specialized servers, as well as the extensive network connecting them. In order to minimize delays in providing computers e.g. to new employees, E&I has developed a standard PC configuration of which several units are always kept in stock, allowing a fully functional new PC to be installed within 24 hours after being ordered.

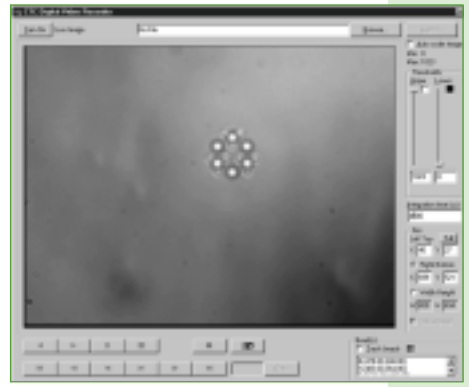


Fig. 1: Graphical user interface written in Visual C++ for a confocal microscope coupled to a CCD camera. The program allows the automated tracking of the image of colloidal beads selected by the user.

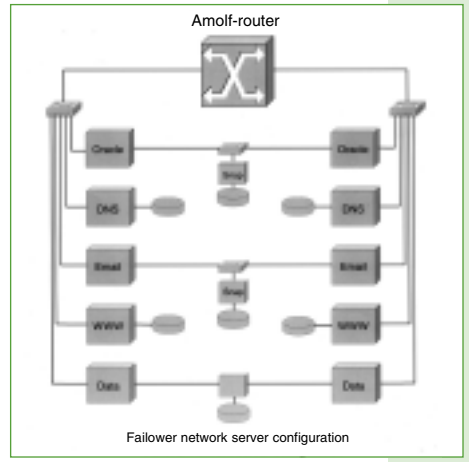


Fig. 2: Part of the AMOLF computer network configuration. All essential servers are duplicated with automatic fail-over functionality, and the attached disk systems are of the RAID5 type, ensuring maximal uninterrupted service.

3.3 COMPUTER AIDED ENGINEERING DEPARTMENT

As many of the experimental set-ups at AMOLF are designed and built 'in-house', the services of the Computer Aided Engineering Department are indispensable. In collaboration with the scientists sketches for new equipment are turned into CAD drawings. Using specialized software packages many physical properties of these designs, like the mechanical and thermal response, can already be tested "in silico" before they are actually produced. The system currently employed by the department allows some of the designs to be directly translated into control code that can drive computerized machining tools available in the Mechanical Workshop.

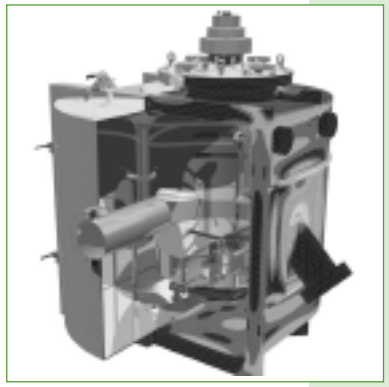


Fig. 1: A CAE stress analysis of a vacuum-coating vessel.

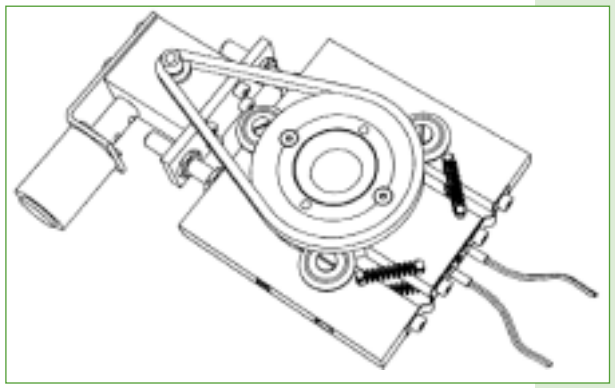


Fig. 2: Design of a heated rotating sample stage. For a picture of the actual equipment, see the section on the Mechanical Workshop.

3.4 MECHANICAL WORKSHOP

The Mechanical Workshop is responsible for building much of the state-of-the-art experimental equipment employed at AMOLF. In close collaboration with the Computer Aided Design Department mechanical designs are realized using a variety of techniques such as diamond cutting, vacuum brazing and conventional as well as electron beam welding. Computer-controlled machining equipment enables CAD drawings to be translated efficiently into machined components. These encompass standard milling machines and wire as well as micro electrical discharge machines, allowing e.g. holes with diameters of several micrometers to be made. The Mechanical Workshop also serves as a training ground for promising apprentices and graduates of the mechanical engineering schools to prepare for further careers in an environment where a steady stream of unique and challenging mechanical designs have to be produced to high specifications.

Fig. 1: A multi-port vacuum vessel

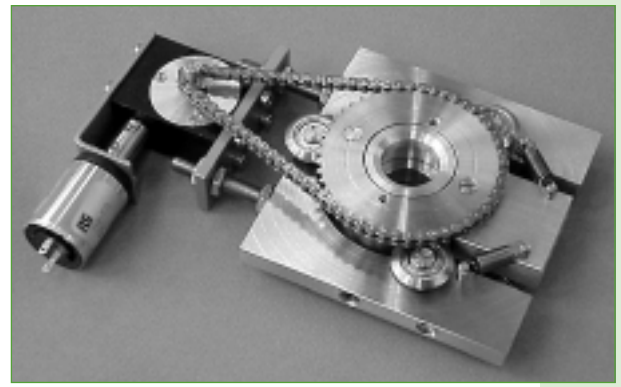


Fig. 2: A heated rotating sample stage. For the original design, see the section on the Computer Aided Engineering Department.

3.5 THE INFORMATION SERVICES

The Information Services at AMOLF collects and assembles primary and secondary materials to stimulate and support research. The collection has a special focus on selected areas of atomic, molecular and optical physics, condensed matter physics and biophysics. It includes about 5000 books, around 70 journals (online and print version) and articles written by AMOLF researchers (until now around 4500), which are available online via the library catalogue and other databases. Materials not held in the collection, needed for study or research by students or researchers, may be requested through the Interlibrary Loan Services or bought.

The Information Services is responsible for constructing and maintenance of the AMOLF website (internal and external) and database building. The AMOLF website is an important source of information for internal and external users. Therfore much effort is invested in continuously updating and extending the site.

The institute submits yearly about 120 manuscripts. Prior to submission an internal referee and the director review these manuscripts. The library administrates the outgoing manuscripts. For funding proposals we have a similar procedure. Scientific publications are an important means of interacting with the outside world and our library is the portal of this.

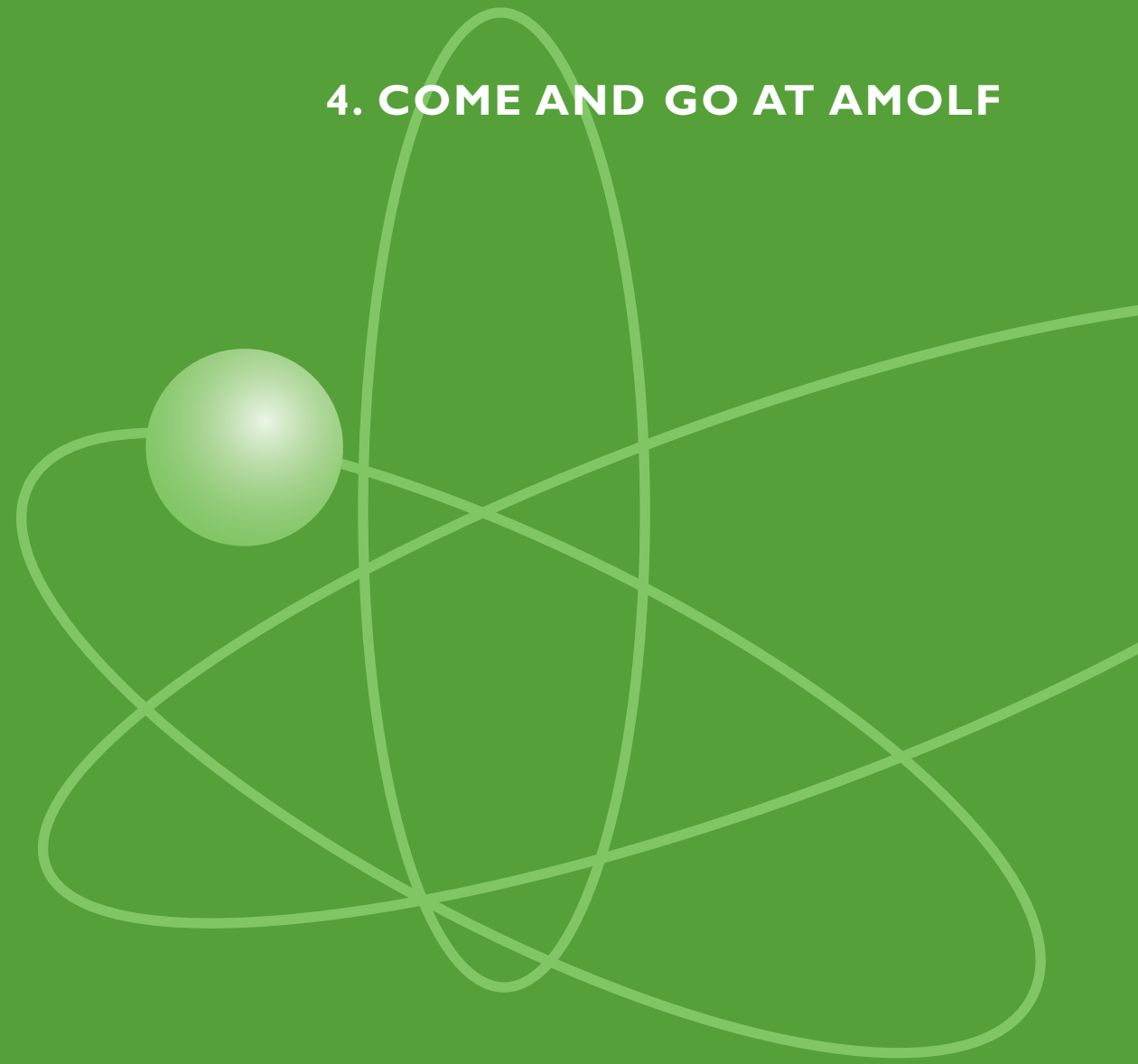
3.6 OFFICIAL DOCUMENTS AND HOUSING FOR FOREIGN EMPLOYEES

Working abroad confronts foreigners with new rules, procedures, bureaucracy and cultural differences. To prevent unnecessary stress, AMOLF assists her foreign guests and employees actively with obtaining compulsory documents, like working permits and visa, and (furnished) housing. The conditions of employment provide financial compensation of moving expenses as well.

For foreing employees, AMOLF applies for the working permits and visa. Moreover, at arrival, the personnel officer of AMOLF assists the new foreign colleague with obtaining a bank account, health insurance, residence permit, fiscal number, etc. The Institute also has a programme for getting acquainted with living in Amsterdam. And, importantly, AMOLF offers foreing employees and their partners a Dutch language course.

It is difficult to find suitable housing in Amsterdam, let alone if you come from abroad. However, most foreign employees and guests are accommodated at approximately 90 addresses, ranging from rooms/studios to family apartments, due to efforts of the travel & housing officer at AMOLF. Most apartments are close to AMOLF and are easy to commute by bicycle or public transport. Short time visitors often stay in the AMOLF villa next to the Institute (see picture).

4. COME AND GO AT AMOLF



4.1 WHO JOINS AMOLF?

AMOLF welcomes yearly about 50 scientists, ranging from project leaders to master students. Details of the application procedure can be found on the homepage www.amolf.nl.

PROJECT LEADERS (1-2 per year)
Every year, AMOLF invites one or two young scientist (typically mid thirties) to start a new - independent - group. The research topics are often related to current research programmes in one of the four departments, but also new directions are explored that might become a theme of a new department. Once the research area is agreed upon, the new group leader is free to select the research projects. Scientific collaborations and sharing of equipment with other groups is strongly encouraged. Together with the department head the progress towards a senior position at AMOLF or elsewhere is frequently discussed. In particular, attention is paid to how to improve the quality of the research projects, how to run a group and how to interact with other groups.

POSTDOCS (~10 per year)
Postdoctoral fellows have to make the transition from running an individual research project (as PhD students do) towards running (part of) a group. In the beginning postdocs often get a well defined project, while later on a more independent attitude is expected, for instance by starting new projects and supervising PhD students. As all scientists at AMOLF, postdocs can make use of all facilities and equipment available at the institute and not just the infrastructure of the group. As discussed on page 65 (section 3.6), AMOLF assists international scientists with housing, insurances, visa and working permits.

PHD STUDENTS (~10 per year)
AMOLF welcomes Dutch and international students to enroll in a PhD program that takes about 4 years. Eventually, the graduation ceremony will be at one of the Dutch universities. Each student has a well-defined research program that is part of the research field of the group. Interactions with other members of the department are an essential part of most research projects, and are further stimulated during combined work discussions. The training program (on the job and special courses) puts special emphasis on presentation skills, project management and the like. Conference visits and other international interactions are seen as essential for a successful PhD program.

MASTER STUDENTS (~5 year)
Master students can do their internship (*afstudeerstage*) in several groups at AMOLF. Students have their own research project, the results of which are presented in a publication or internal report. A PhD student or a postdoc gives daily supervision. The students get a contract in which their remuneration and working hours are described. Please contact Prof. Dr. M. Dogterom to make an appointment (dogterom@amolf.nl or 020 - 6081234).

SHORT TERM GUESTS (~20 per year)
International interactions are essential to keep the large scientific productivity of high quality. We are therefore delighted that a large number of guests visit AMOLF every year. Some come for a relatively short period (1 month) while others spend their sabbatical at AMOLF. Every year we honor two guests with a Joop Los fellowship.

4.2 WHERE DO THEY GO?

The table below gives an overview of the positions of the current employees at AMOLF. It also shows the positions of former employees after they left AMOLF.

POSITION	CURRENT NUMBER	CURRENT AVERAGE AGE	POSITION FORMER EMPLOYEES AFTER LEAVING AMOLF	
Senior scientists	19	43	Full Professor at University	70%
			Industry	20%
			Other	10%
Postdocs	35	31	Academia NL	6%
			Academia abroad	55%
			Industry NL	15%
			Industry abroad	17%
			Unknown	7%
PhD Students	46	27	Academia NL	18%
			Academia abroad	22%
			Industry NL	50%
			Industry abroad	5%
			Public sector	5%
Technicians	45	40	Industry	95%
			Started own company	5%
Other/Administrative support	35	47	--	

4.3 HOW TO GET THERE

By public transport

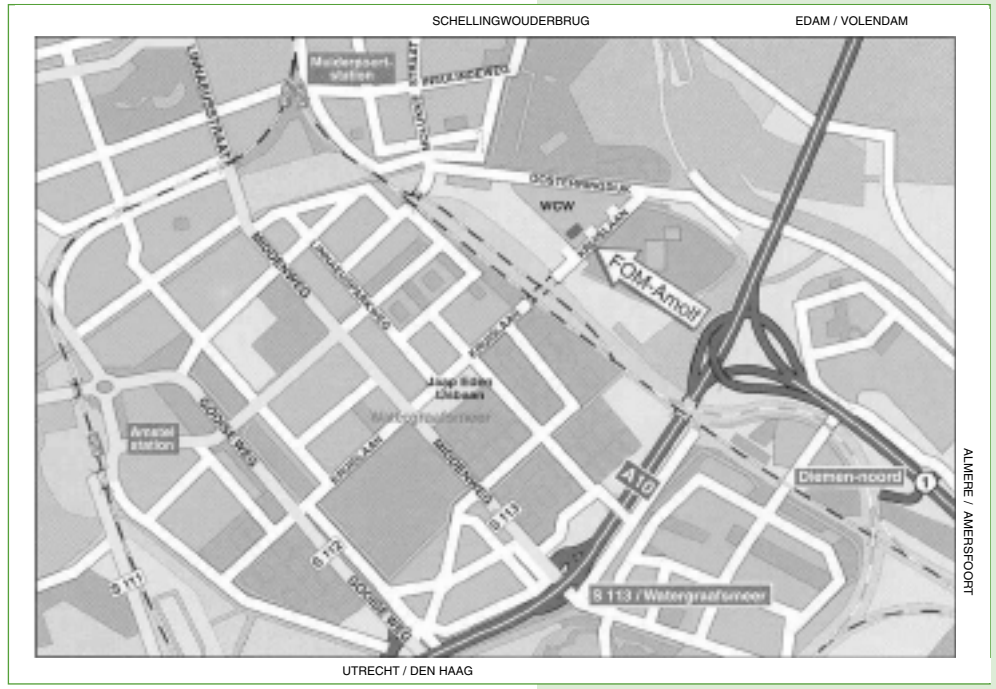
1. From Amsterdam-Amstel railway station:
Take bus 67 to Science Park Amsterdam. This bus leaves every 30 minutes, Monday to Friday. The institute is located on the Science Park Amsterdam grounds. For more information and time-schedule see: www. amolf.nl.
2. From Amsterdam-Central railway station or Amsterdam-Duivendrecht railway station:
Take a local train or subway to Amsterdam-Amstel railway station, from there see 1.
Alternative: take tram 9 at the Central Station to the corner of Middenweg and Kruislaan and walk about 1 km along Kruislaan (direction Science Park). After passing through the railway tunnel you take the first entrance into the Science Park on your left hand side.
3. From Amsterdam-Muiderpoort railway station:
Take a local train to Amsterdam-Amstel station. From there see 1. Alternatively, 20 minutes by foot via Insulindeweg and Molukkenstraat to Science Park Amsterdam.

By taxi

From Schiphol Airport a drive by taxi will cost appr. € 35,-
From Amsterdam-Amstel railway station: € 10,-
From Amsterdam-Duivendrecht railway station: € 20,-
From Amsterdam Central Station: € 12,50

By car

All motorways to Amsterdam lead to the ring road called 'Ring' (A10). From Utrecht/Den Haag/ Schiphol/Haarlem or Zaandam, join the 'Ring' in the direction Amersfoort. From Amersfoort, join the 'Ring' in the direction of Utrecht/Den Haag. Take exit S113/Watergraafsmeer, head for Watergraafsmeer/Science Park. Follow signs 'Science Park'.
On the 'Middenweg' turn right at the 'Kruislaan'. After passing through the railway tunnel you take the first entrance into the Science Park on your left hand side.



4.4 HOW TO APPLY

PhD and postdoc positions at AMOLF

What is AMOLF?
The FOM Institute for Atomic and Molecular Physics (AMOLF) is one of the five national research institutes of the Foundation for Fundamental Research on Matter (FOM).
The Institute is located in Amsterdam, in the Science Park in Watergraafsmeer.
AMOLF employs approximately 200 people, of whom about half are scientists (including PhD students and postdocs).
14 employees are professors at various Dutch universities.

What does AMOLF do?
AMOLF does fundamental research in the following areas:
• Experimental Life Science inspired Physics: investigating biological systems from a physicist's point of view with techniques such as optical tweezers and mass spectrometry
• Theoretical Life Science inspired Physics: theoretical investigation of e.g. biological networks, protein folding and biological materials
• Femtophysics: investigation of the femtosecond dynamics of diatomics to biomolecules
• Nanophysics: the atomic scale synthesis, manipulation, and modification of surfaces and thin films with novel opto-electronic applications
• Explorative research: including development of new mass spectrometry and other imaging techniques for the study of paintings and other art objects as well as researching the creation and of antihydrogen atoms

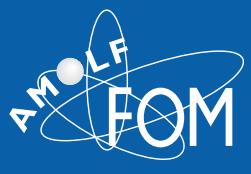
Why work at AMOLF?
AMOLF provides a dynamic environment where advanced research is performed in compact groups comprising around 5 postdocs and/or PhD students per group.
The work atmosphere is informal and open in nature, and there is plenty of interaction between the different groups in the institute.

Interested in working at AMOLF?
Check our website www.amolf.nl for updated vacancies. In addition, "open" applications are always welcome.
Applications can be sent to the group-leader of the research group you are interested in or directly by e-mail to application@amolf.nl or by letter to our postal address:
Kruislaan 407, 1098 SJ Amsterdam.

AMOLF FOM Institute for Atomic en Molecular Physics

Colophon

Lay-out and cover design:
Wies Oldenziel
Printing:
Zwaan printmedia
Edited and coordinated by:
Erny Lammers
Pieter Rein ten Wolde
Cover:
Huib Bakker



Institute for Atomic and Molecular Physics