Condensed Matter and Optical Physics (COMOP)
Focus document 2013

FOM-COMOP
The FOM advisory committee ‘Condensed Matter and Optical Physics’ (FOM-COMOP for short) represents the atomic, molecular, optical, soft and hard condensed matter physics communities in the Netherlands. FOM-COMOP advises on matters concerning research and research policy, and in doing so works together with the FOM working groups Nanophysics/-Technology, Physics of Life Science and Phenomenological Physics. COMOP researchers contribute to four out of five strategic directions formulated in the National 'Sectorplan' for Physics: Quantum Universe, Complex Systems, Liquids & Solids and Energy.

COMOP research centres on the understanding and manipulation of the structural, transport and optical properties of atoms, molecules, soft and hard condensed matter and materials. This research is both curiosity-driven - seeking to deepen our fundamental understanding - and aimed at meeting the need to develop advanced methodology, new applications and new device concepts.

Ten-year vision: next-level, emergent functionalities through control of organization
COMOP systems (soft- and hard condensed matter and materials, molecules and light) are ubiquitous. In the coming decade, we foresee a jump in control over the (often) emergent functionalities of such systems, right across the broad spectrum of COMOP physics. This will bear fruit in fundamental science and all the more in our ability to exploit these properties. These developments result from three interrelated activities.

Firstly, theoretical and simulation-based approaches for describing complex matter at a high level of precision and fidelity to reality have reached an unmatched level of sophistication and dependability. The computational approach has become a full-value partner for experimental physics in determining the structure-function relationships that underlie progress in science and technology.

Secondly, our ability to generate controllable and stable structures and architectures across the board from atoms, molecules and complex liquids to crystalline (nano)materials now provides a stable basis from which to enter the world of non-equilibrium situations and states.

Thirdly, new experimental tools exploiting exquisite sensitivity and resolution (in space, in time, in energy, with respect to control of phase) are coming of age, and are now able to deal with real systems under increasingly realistic conditions of complexity.

There are many recent illustrations in COMOP research of how progress in curiosity-driven areas can form an effective launch-pad for the development of new approaches, materials and even technologies which find their application in key societal areas spanning from information to food and from water to energy. The FOM-COMOP committee sees a role in identifying and resolving fundamental bottlenecks that separate potential applications from their effective realisation to the benefit of society.

COMOP now
COMOP research in the Netherlands is a highly active area, encompassing the work of researchers in the universities, FOM Institutes AMOLF and DIFFER as well as in numerous industrial laboratories and a growing number of public-private research institutions. The Netherlands has a significant impact and contributes with high quality science to COMOP physics in the global arena.

COMOP’s research topics encompass the investigation of ultra-cold atoms, smart-, bio- and self-organizing molecules, polymers, colloids, solid state systems with different levels of crys-
tallinity and emergent phenomena born out of complexity in structural, charge, spin, and orbital degrees of freedom and their coupling to external light, electric and magnetic fields. Materials such as organic-inorganic hybrids, complex hetero-structures and new magnetic structures are important subjects of study, as are the techniques required to master their generation. Together with transport and thermodynamic measurements, structure determination (both in reciprocal and real-space) and spectroscopy, the latter conducted over the full electromagnetic spectrum form important COMOP experimental methodologies. This makes COMOP an important user of and also host of high technology facilities. Importantly, COMOP stimulates, develops and employs a wide range of theoretical and simulation techniques.

One of the strengths of the COMOP field is its diversity, spanning aspects of materials science. Leaving aside large scale plasmas, COMOP covers all other states of matter, and spans a large range of length, energy and timescales. To effectively focus efforts towards the twin challenges of scientific excellence and societal relevance, continuing cross-fertilization between the different sub-fields of COMOP is essential, as is the identification of promising new directions in which this synergy can be harnessed to force breakthroughs. This document takes the next step in doing this, following up on an earlier focus document, drafted by FOM-COMOP and adopted by the FOM board in 2009.

Important themes across soft-hard condensed matter and AMO physics

Here, this FOM-COMOP focus document highlights some of the most promising developments and new directions in three main research areas, before bringing together their promise in the context of applications and value to society and closing with a forward looking summary of ambitions for the coming decade.

1. Soft condensed matter

Soft condensed matter (SCM) focuses on understanding the structure and resulting properties of many-body systems that are neither crystalline solids nor simple liquids. Examples include colloids, nanoparticles, emulsions, polymers and surfactants. SCM is found everywhere in nature, providing building blocks of biological organisms: blood and other cells, DNA, proteins etc. and is used in drug delivery systems and consumer products such as cosmetics, paint, plastics and food. Soft materials flow or deform easily under external forces because they are ‘mesoscopic’: made of objects that are large compared to simple molecules, but generally too small to see with the naked eye. These mesoscopic components often organize themselves via self-assembly into highly complex structures with remarkable mechanical, optical, or other functional properties. SCM is heavily embedded in the chemical and food industry; Netherlands’ colloid science is world-leading both in resolving fundamental issues as well as in creating added value in dairy or coating/painting industry.

SCM research is highly multidisciplinary and brings together physics, chemistry, mathematics, computer science, biology and energy research. SCM physics has made tremendous progress enabled by the high level of control in synthesis and fabrication, and by enormous computer power in combination with faster algorithms for computer simulations, and by powerful tools to characterize, study and manipulate soft matter systems, such as advanced confocal microscopy, electron microscopy, and scattering techniques.

FOM-COMOP expects to witness further progress in the understanding of collective behavior such as phase transitions, nucleation, gelation and the glass transition, as well as in active (self-propelling) particles with links to biological systems. The fields that are at the interface between soft- and biological matter and that are very actively studied in the Netherlands are statistical physics; non-linear and out-of-equilibrium dynamics; self-assembly and self-organization of complex systems; crowding, compaction and jamming. The coming years will see a continuing interaction between these different fields, with the main question remaining
how the organization of the building blocks leads to the function in the form of specific mechanical or optical properties. Novel colloidal building blocks with new functionalities will be created, enabled by advances in chemical synthesis, leading to particles with - for example - specific, directional, patchy interactions or particles influenced by external stimuli. Smaller colloids, benefitting from advances in surface chemistry will provide unprecedented possibilities for generating nano-structured materials with plasmonic, photonic, and catalytic properties. One of SCM's future aims is to explore these new directions which complement the NANO research theme, and which may in addition contribute to solutions for the global energy problem.

In the last few decades, soft matter systems have played a pivotal role in understanding the fundamental principles of equilibrium many-body systems. We are now witnessing a paradigm shift from equilibrium to non-equilibrium systems. In this area, many new possibilities are opening up due to both novel theoretical tools and new experimental developments: we are only starting to understand (bio-)polymer networks, composite polymer systems, and suspension rheology, but also for instance the coupling of hydrodynamic flows with fluctuations. Future progress here will provide better insight of the underlying principles in non-equilibrium systems, e.g. glass and gel formation, homogeneous and heterogeneous nucleation, driven systems (granular systems), coupling with fluctuating solvents (critical solvent fluctuations, hydrodynamic interactions), and active matter consisting of self-propelling particles that convert chemical energy into movement. These developments will bring SCM close to the physics of life research theme.

2. Hard condensed matter

Hard condensed matter (HCM) physics focuses on the understanding of structure and properties of many-body systems in the solid state, including surface- and interface effects. Understanding the quantum mechanics underlying the collective behavior of assemblies of particles opens up countless possibilities to discover novel states of matter, to develop new materials and new device functionalities. HCM's main aim is to explore this emergent space, and to expand and exploit these possibilities, and in doing this HCM acts side by side with FOM-NANO.

HCM has not only a central position in physics, but is also firmly embedded in the industrial landscape in the Netherlands, as can be seen by strong HCM-related activities in industrial laboratories, as well in numerous co-operations between academic research players with leading industries. Common to all these activities is - at one end of the spectrum - the ability of the HCM community to translate application requirements into fundamental research topics, and - at the other end of the spectrum - the creative and resourceful exploitation of fundamental solid state physics knowledge in commercially viable applications and processes.

In the last few years, great progress has been booked in the development of new materials within the HCM domain. Complex (oxide) heterostructures, novel oxides, organic-inorganic hybrids, magnetic structures, graphene, topological insulators, quantum wires, break junctions, and new meta-materials with tailored optical properties are developing fast in an efficient 'one-two' with condensed matter theory. Looking forward, it is clear that the trend to increasing complexity - as seen in the juxtaposition of materials systems with widely differing electronic, magnetic, dielectric or topological properties - will continue, but with increased effort to retain enhanced control. Not only new approaches are important, but also the continued improvement of existing (nano)synthesis techniques and facilities will be major focal point, so as to maintain sustainable sources of systems with new or improved functionalities. Improved and new experimental techniques have always played a role at the forefront of condensed matter physics. Traditional transport and spectroscopic techniques are nowadays complemented by many new methods, among which ultrafast optical, (E)UV & X-ray probes, high-precision spectroscopy using frequency combs and ultra-microscopy stand out. Such
techniques have a strong track record in uncovering detailed information on structure as well as properties at the single-particle and collective level, be they in the electronic, spin or orbital sectors. The coming decade will see further developments here, with increasing use being made of out-of-equilibrium states so as to disentangle cause and effect in complex quantum many-body systems and to explore the intrinsic speed and energy usage limits for switching processes of relevance to the storage and manipulation of information.

The increased understanding of emergent collective behaviour in many-body quantum systems from theoretical research on strongly-correlated states of matter has been a continued source of new developments in HCM. Examples of materials systems at the forefront include topological insulators and low-dimensional systems such as (self-assembled) wires. Also systems in which the quantum degrees of freedom in the form of electron spins, photon spins, but also new types of (quasi-particle) excitations as Majorana fermions have controllable entanglement are of great interest, providing a pathway towards the realization of – topological- quantum computing devices. The high-end theory underlying many of these developments will continue to be a focus in the coming decade. As many body physics advances, the effects will be felt beyond solid state physics. Molecular physics, soft matter and complex systems in general will benefit from advanced simulation methods being developed on the basis of quantum information theory. The transposition of mathematical methods originating from high-energy and string theory is starting to show great promise in the context of non-Fermi liquids and the still open problem of high-temperature superconductivity.

3. Atomic, molecular and optical physics

Atomic, molecular and optical physics (AMO) addresses matter at a fundamental and advanced level. The scientific aim of AMO can be summarized as predicting the behavior of electrons, nuclei and photons in situations ranging from single molecules to complex large biomolecules and from high precision metrology to the spatial manipulation of optical beams. AMO contributes to progress in methodology that finds applications in condensed matter and other areas of physics, as well a contributing to applications outside physics. AMO physics is in many aspects a mature field of science. As such, most if not all present developments have evolved from monitoring to manipulating, from treating isolated to coupled systems, and from well-defined to open experiments, in which parameters are optimized on the fly.

In recent years, atomic and molecular physics has evolved towards complexity and to systems under extreme conditions. In cases such as the combination of ultra-cold atoms with macroscopic/mesoscopic structures and the realization of controllable and strong interactions at the single atom level, the full potential of these approaches still lies ahead. As such, manipulation of atomic and molecular systems related to high-precision physics, both for metrology but also probing molecular interactions at very low energies, will also continue to see significant development. In this context, super-resolution lasers based on frequency combs, and their extension towards ever shorter wavelengths is highly promising for the coming years. This field may establish further links towards fundamental questions that were previously limited to the realm of high energy physics. In addition, recent developments in quantum information in particular the search for reliable qubits, but also in the field of quantum magnetism point the way towards future interaction zones between HCM with AMO physics.

Molecular physics continues to uncover insights into very fundamental issues related to systems such as those found in living matter: the nature of coherence in biological systems, the transformation of light or ATP energy to molecular action or molecular change. Here, experimental studies from the single-molecule level up to supra-molecular assemblies will combine to increasing effect with ab initio theoretical modeling and molecular dynamics simulations in a multiscale approach. The coming decade will witness further steps towards visualization of molecular motion, such as in chemical reactions and under enzymatic activity, both on the
level of nuclear motion and with steps towards understanding electronic motion on its own attosecond timescale. Also in the AMO field, the worldwide developments in ultrafast and coherent X-ray sources, but also the development of ultrafast electron sources for time resolved electron diffraction, are providing new tools which have to be complemented by smart experiments and judicial choices so as be able to answer fundamental questions on the physical chemistry of bio-reactions and to study systems out of equilibrium. The field of coherent control has pushed the potential of manipulating the phase, intensity, and/or polarization of electromagnetic fields from steering few-atom systems to obtaining novel information on much more complex entities, sometimes in combination with self-learning algorithms. The manipulation of the spatial degrees of freedom has seen a recent surge of interest and possesses a lot of potential. Coherent control is expected to produce new applications in the coming decade. Although not directly connected, the manipulation of electromagnetic radiation using sub-wavelength holes or other meta-materials is pushing the combination of spatial resolution and wavelength selectivity in super-resolution applications in another combination of HCM and AMO physics, which also has clear connection to FOM-NANO. Summarizing: AMO research will progress towards more complex systems, possibly self-organized, to be found in layers and in both liquid and solid phases - in this sense closing the complexity gap with the fields of soft- and hard condensed matter, while keeping the resolution and the information content that is so characteristic of gas phase atomic and molecular physics in the past.

4. Societal applications
The Dutch COMOP community's researchers are regular contributors to the high impact journals defining the topmost level of science in the field. From this strong scientific basis, COMOP has and will continue to contribute to scientific progress and to technologies of relevance for society. Intrinsic to much COMOP research is a large degree of complexity, which is also a characteristic of industrial and societal problems, such as energy and climate issues. In this context, FOM-COMOP underlines the continued importance of the education of young researchers well-trained in SCM, HCM and AMO physics, as a resource of scientists able to understand, study and describe complex issues, and as a group of future knowledge-based employees able to set this knowledge and the approaches learned to work in the service of society. COMOP has leadership in the use of high tech methodologies and contributes to international user facilities, which makes COMOP research an innovation base for future industrial and infra-structural activities. COMOP will contribute to the areas of information technology and the energy transition. In the former, whereas in the past information technology was limited to speed and miniaturization, in the coming decade integration and energy costs will be as important. In the latter, COMOP will continue to play an important role in enhancing the future use of solar energy and in reducing energy demand in information technologies. We expect that in the years to come, COMOP will contribute significantly to an increased insight into the physics of complex systems both in equilibrium and out-of-equilibrium conditions. This progress is based on the development and use of advanced international user facilities coupled to novel mathematical and theoretical methods. COMOP research will develop new device principles applicable in qubits and sensors with unparalleled accuracy. A bundling of research knowledge and expertise distributed broadly across COMOP will be of importance for the success of the planned public-private partnership with ASML on nanolithography. In addition, COMOP will continue to contribute to smart molecules and materials research, helping to tackle the issues of scarcity for critical elements in large volume applications, thus reducing the environmental costs of devices and technologies. Nationally, the topsector policy is becoming a reference point to fund and classify research with attention to the application horizon and with priorities in themes and research defined in com-
bination of academic and industrial partners. In the coming years it is expected that COMOP research will contribute to a number of these topsectors (TS). COMOP research is logically part of the TS High Technology Systems and Materials (HTSM), including the direction of Advanced Instrumentation within HTSM. The TS Chemistry with its interest in new smart materials and catalysis is also naturally connected to SCM and AMO research. The TS Energy is divided over seven different Topconsortia voor Kennis en Innovatie (TKI) of which the TKI Solar Energy is most closely linked to the SCM and HCM activities within COMOP. Finally, FOM-COMOP notes that methodology development that is common to SCM, HCM and AMO research has found and will find its way frequently into the Life Sciences and sometimes to Health research, which presents a connection to the TS Life Sciences and Health. On a European scale, Horizon2020 has defined grand challenges. COMOP research will be able to contribute to calls in many of these very broadly defined challenges.

5. Ambitions

The ubiquitous nature of the subject matter (gases, liquids, solids) makes COMOP research a central topic as regards both fundamentals of physics, as well in facilitating new techniques and developing new applications possibilities. The ambition of COMOP is to maintain the position Dutch research has as a world leading player in soft condensed matter research, hard condensed matter research, atomic, molecular and optical research and in the broad field of material science.

FOM-COMOP sees a key role for the community in the following activities:

- helping to force progress in areas in which fundamental processes and factors need to be mastered so as to bring potential applications to realization;
- providing continuity in key research skills and technologies of benefit to the Dutch and COMOP scientific communities;
- acting as a bridgehead between physical sciences in the Netherlands and national and international user facilities.

The COMOP community will have succeeded in her mission in the coming five to ten years when her research has been found not only to be of the highest quality and originality, but also possesses a healthy balance between combining fundamental science with long application horizons with applications-driven research requiring the effective elimination of fundamental bottlenecks in fields such as information and energy, food and water.