

# Strategy documents

Physics research communities  
Round table Physics  
2020

## Nano, Quantum and Material Physics



## 1. Scope and definition of the research community

The key research areas covered by the research community (RC) Nano, Quantum and Materials Physics (NQMP) are the understanding and potential manipulation of electrons, photons, atoms, molecules, and materials. This includes interactions between (quasi-)particles with charge and spin, their interaction with external fields, their excitations, as well as the dynamical processes that they induce. Properties that arise from confinement effects in nano-materials, as well as from collective interactions and order phenomena, are also at the center of the NQMP interest. Since the properties of materials not only depend on the constituent building blocks, i.e. the atoms or molecules, but also on the interactions between them, different properties can appear at different length scales, in different dimensions, and even in differently shaped materials. This makes the research field of nanoscale and quantum matter extremely rich in terms of fundamental physics, and provides a huge potential for current and future device applications. The NQMP RC brings together the traditional fields of atomic, molecular and optical physics, hard condensed matter, materials science, interface physics, physical chemistry, soft matter, and nanoscience.

## 2. Vision for the next ten years

The NQMP RC identifies three areas in which major breakthroughs, both scientific and societal, are imminent: Quantum technologies, Green ICT, and the Energy transition. These breakthroughs promise transformative solutions for an energy efficient and democratic access to both resources and knowledge, and provide natural focus points for NQMP research in the near future. The ambitions and goals of these three areas are as follows:

### Quantum technologies

Quantum technology aims at controlling the quantum states of matter, and to integrate them in platforms suitable to address societal challenges. With recent advances, quantum platforms are now beginning to move beyond the realm of scientific laboratories, repre-

sented a potentially highly disruptive technology, with unprecedented opportunity for society but also with threats to existing security that need to be addressed. Quantum computers, quantum simulators, quantum networks, and quantum sensors hold promises to perform calculations fundamentally faster than a classical computer, to simulate problems in physics and chemistry that cannot be solved in a classical way, or to provide fundamentally secure communication, giving rise to exponential advances in many fields of research and technology. The increasing ability to control the quantum mechanical properties of particles or excitations of isolated systems, such as of electron spin and nuclear spins in solids, of quantum superconducting circuits, of cold atoms and molecules, ions, quantum degenerate gases, forms the basis for qubits and the corresponding quantum technology. The possibility of harnessing macroscopic degrees of freedom also offers quantum materials as platforms that can provide physical implementations of quantum systems for higher coherence.

### Green ICT

Current information technology is based on electronics for computation, photonics for signal transport, and spin for memory. The current energy consumption of ICT already stands at > 7% of current world electricity use. Fundamental breakthroughs are needed to overcome the energy and bandwidth limitations of contemporary technology. A first bottleneck is the so-called von Neumann architecture of computing in a CPU separated from a memory, that requires up to 105 times more power than the human brain. The second bottleneck is the slow inter-conversion between light, spin, and electrons. The field foresees innovations in adaptable electronics for energy-efficient computing, materials that change their state or act as physically configurable networks, physics-based machine learning; and brain-inspired architectures such as hardware implementations of deep learning networks with particles or photons, reservoir computing, and analog signal processing based on wave physics. The energy consumption problem in computation and memory could be overcome by progress in superconducting computers. Generally, this theme pursues new concepts in processing and controlling information, to interconvert charge, excitons, photons, phonons, spins, and magnetic excitations, at ultimately low energy scales (aJ/bit) and ultrafast timescales needed for ICT.

## The Energy Transition

The energy transition of the coming decade requires major fundamental breakthroughs in energy generation, conversion, and storage. The circular economy aspects of materials deserve more attention, as well as new solutions for recycling, waste management, corrosion, etc. On the interface of chemistry and physics, there are important challenges towards developing non-toxic materials and devices and for further increasing the efficiency, sustainability and durability of widely used processes. For instance, in the domains of photovoltaics, thermoelectrics or the hydrogen economy, essentially new concepts are needed to significantly overcome the currently achieved efficiencies. This will require a fundamental understanding of new materials, and hybrid or tandem device geometries. Photonic up-/down-conversion with nanomaterials may extend the applicable solar spectrum and find important applications in health care, e.g. imaging-contrast nanoagents, nano theranostic nanoplatfroms, and immunoassays. Another focus is the development of new energy storage materials for batteries and supercapacitors, and the harnessing of chemistry and photochemistry in nanoscale confinement, for instance in the framework of solar fuels. Sustainable, even passive, cooling, through the clever engineering of thermal radiation management or implementation of material and energy sustainable light sources and optoelectronic/photonic devices can also lead to substantial energy savings.

The NQMP community in the Netherlands is positioned to address these societal challenges. The binding theme of the NQMP community is the understanding of the physical properties that emerge in matter and how these can be harnessed in useful applications. By its very nature, this research aligns theory, experiment, materials synthesis, nanofabrication, and novel instrumentation with extreme resolution. Open challenges increasingly deal with the understanding of emergent behavior (system properties that are different from those of the constituents) in systems of larger complexity, such as in supra-molecular systems and biomolecules, complexity in soft and hard condensed matter and strongly correlated quantum systems, and the design of emergent behavior at will, such as in quantum simulators, metamaterials and neuromorphic hardware systems.

## 3. Scientific challenges/themes

Technically, to achieve the visions described in 2, the following challenges need to be tackled:

### Quantum control and transduction

In order to achieve the ultimate promise of quantum technologies, several challenges need to be addressed. Only by improving coherence and scaling in quantum simulators, networks, computers, or sensors, the pathway towards applications can become feasible be expected. For this, new concepts will need to be developed, and the boundaries of quantum coherence and control will need to be expanded. In order to address relevant problems, maintaining the coherence of scalable building blocks up to relevant system sizes is a crucial goal. A second key concept will be the connectivity of quantum technologies: To achieve functionality which is not possible in one system alone, it is necessary to interface for instance superconducting quantum computers, optical quantum networks, and atomic and molecular quantum gases. This concept of *quantum transduction* between different degrees of freedom, such as spins, photons, mechanical vibrations, phonons, and radio-frequency signals will play a crucial role in future interconnected quantum technologies, and it is a field currently in its infancy. New physical concepts bridging all fields of NQMP will need to be developed to address this challenge, including the control of materials at the nanometer scale using nanotechnology, and the development of new tools for advanced control of the quantum excitations in the different physical systems.

### From single atoms to complex matter

Developments in atomic, molecular, optical and condensed physics can address the ambitions described in section 2 at a fundamental level, using advanced and highly precise tools. The physics questions and challenges in this area have evolved towards complexity (phenomena that arise when atoms or molecules are combined in a highly controlled way), and to understanding systems under extreme conditions, such as in high magnetic and electric fields and at high pressure, at ultrashort time scales or extreme temperatures. Monolayers of atoms, on well-chosen substrates, can become superconducting. Ultra-cold atoms, ions, and molecules

can form quantum gases that exhibit exotic phase transitions. Cold atoms, as well as artificial atoms and color centers in protected solid-state environments, can be combined with macroscopic/mesoscopic structures, and have seen the realization of controllable and strong interactions at the single and few-particle level. Novel spectroscopic methods with extreme spatial, temporal and energy resolution need to be achieved to probe quantum systems with exquisite detail and to explore the boundaries of fundamental physics.

### Materials design and engineering

Engineering materials at the nanometer scale, or even at the scale of a single atomic layer, allows ultimate control of devices for data storage, logic or information processing but also for energy harvesting or storage. Quantum materials and nanostructures derive unique properties from quantum confinement, many body interactions, topology, and collective excitations. Understanding the fundamental principles that underlie the emergence of materials properties from their microscopic constituents drives the development of novel nano-materials as well as their potential in technological applications. The possibility to assemble new materials a single atomic layer at a time has led to exotic physics such as relativistic Dirac spectra, topologically insulating states, light-matter interaction with confined excitons and novel spin physics on the basis of so-called 'valleytronics'. Our theoretical understanding of the different transport processes in materials is fragmented and developing consistent theories for these and other exotic phases of matter (such as high  $T_c$  superconductivity or Non-Fermi liquid behavior) is expected to render substantial gains towards energy-efficient device concepts

### Advanced instrumentation and research infrastructure

For all of the challenges above, the development and availability of powerful new tools that allow us to extend our knowledge to a wider range of length and time scales is essential. The possibility to overcome current technical limitations in spatial, temporal or energy resolution is often connected to developments in materials control and device engineering. New developments that allow scanning over several orders of magnitude in space, time or energy using a single setup would bring new strategies to investigate the phenomena that

emerge at specific length scales (nano-, meso- or macro-scale). To use this knowledge to build devices, further developments in nanoscale fabrication and analysis techniques (NanoLabNL), large magnetic fields (HFML) and intense pulsed (far) infrared free-electron lasers (FELIX) are needed as well as novel, lab-based X-ray sources, ultrafast electron techniques and deterministic single-particle delivery.

### Data-driven and machine learning approaches to NQMP

As instrumentation and measurement technologies advance, the availability of huge data sets as well as the still growing availability of computational power opens the door to data-driven approaches/methods to design and tailor quantum materials, metamaterials, soft materials and complex functional materials. Moreover, new developments in quantum machine learning enable the simulation and study of much larger and more complex quantum many body systems, both in and out of equilibrium that were inaccessible before. This includes novel algorithms for simulating massively entangled states on classical computers and new (hybrid) algorithms to be exploited with quantum computers. We anticipate that both approaches can substantially speed up the development of this field.

## 4. Application perspective (incl. societal challenges)

Via public-private partnerships the NQMP field is traditionally strongly connected to the large Dutch companies in ICT, semiconductor technology, lighting, health and high-tech systems and materials, e.g. ASML, NXP semiconductors, Philips, Signify, Lumileds, DSM, JEOL and FEI-ThermoFisher. Further, the community is defined through an entrepreneurial spirit, where researchers apply fundamental concepts from the lab to develop products that meet a societal need. This excellent connection is evident from the large number of IPP/PPS programs (NWO-ENW), as well as TTW OTP and Perspectief projects. In these, industry co-funds academic groups in NQMP to realize breakthroughs in solid-state lighting, semiconductor manufacturing, and applications (e.g. solid state lighting and photovoltaics), materials screen-



ing and characterization of materials by spectroscopy, electron microscopy and scanning probe techniques, and so forth. Other striking examples are recent initiatives such as the ARCNL institute, which combines new impulses from fundamental academic research within industry-driven questions in the field of advanced nanolithography. It is evident that also in the coming 10 years the NQMP field will strongly contribute to applications in these domains, driven by new insights in photonics, spintronics, novel solid-state materials, and high-tech instrumentation. Also, the emerging field of quantum technologies holds significant promise for applications, as signalled by the PPS research in MESA+, QuTech, QuSoft and QT/e, with Microsoft, Intel, KPN, and significant initiatives with large application perspective emerging in the area of energy. While conventional silicon photovoltaics is a market cornered by Asia, there is significant application potential for novel materials and light management strategies for photovoltaics (AMOLF, UvA, TUD, UT), as well as their implementation into real devices (ECN, RuG, VU, TU/e), solar fuels (Differ, WUR, UU) and battery materials (UT, TUD, UU).

NQMP provides the fundamental basis for the key enabling technologies identified by the Dutch government (Kennis- en Innovatieagenda 2018-2021) i.e. photonics, advanced materials, quantum technologies, nanotechnologies, and emerging & fabrication technologies, and is also represented in several others, such as artificial intelligence (neuromorphic hardware,). A diverse range of societal challenges identified in the Kennis- en Innovatieagenda crucially rely on fundamental breakthroughs that must come from the NQMP community. In particular, we expect significant contributions to energy and sustainability, on the basis of new materials and light management for photovoltaics, battery materials, electrochemical storage and conversion, as well as new technologies for green ICT. Photonics, neuromorphic hardware that removes the energy and bandwidth bottlenecks of digital von Neumann computing architectures and enable hardware based deep learning, as well as hybrid technologies that combine photons, spins and excitons in novel materials, have the potential to significantly reduce the energy consumption of ICT. Also, NQMP will contribute to solving challenges in security (secure quantum technologies, photonics, sensing), and agro, food & water (e.g., sensing, spectroscopy, nanochemistry).

## 5. Strengths and infrastructure in NL & international perspective

The NQMP field is strongly rooted at all Dutch universities, where condensed matter physics, quantum physics and optics have traditionally been cornerstones of research and education, and where there is a close link between research and education in chemistry and physics. There is a high degree of organization of research and infrastructure agendas through small-size programs (program portfolio below) and national initiatives. For instance, the significant national investment in nanotechnology (through NanoNed, NanoNextNL and NanoLabNL) and instrumentation (via NWO Groot's large investments) have resulted in a large and nationally coordinated basis of installed nano- and materials infrastructure (TU/e, TUD, UT, RUG, AMOLF), which are also accessible to partner universities. The NWO institute DIFFER is specifically dedicated to energy research. The efforts in quantum physics, in as far as geared at quantum information and communication are similarly strongly organized through the National Agenda for Quantum Technology (NAQT), QuTech, QuSoft, QT/e, MESA+, the Kavli Institute, the Zwaartekracht program Quantum Software Consortium, and the national alignment towards the EU quantum flagship, while national consortia and agendas have also emerged for photonics (PhotonDelta), energy (SolarLab) and materials (NWO Materials: Made in Holland). An important strength is that the NQMP field is traditionally closely linked to high-tech industry in nanotechnology, materials science, instrumentation and photonics, such as ASML, Philips, NXP, ThermoFisher-FEI. The international facilities of HFML and FELIX also play a key role in contributing, not only to the Dutch research landscape, but also to the global portfolio of large-scale research infrastructures

## 6. Specific challenges for the community

The structural funding from the government for large infrastructure facilities, such as NanoLabNL and HFML-FELIX, is vanishing. It is essential to keep these large infrastructure facilities up-to-date, as they are an enabling platform for a very large body of research in

physics, materials science, life science and chemistry, as well as forming a necessary resource for high-tech SMEs. The community faces the challenge to find alternative funding sources to maintain the facilities at the state of the art. Funding this system from ad-hoc funding opportunities carries a great risk and strongly compromises the long term planning of ambitious research projects.

## 7. Research portfolio

Organization	# NQMP members
AMOLF	7
ARCNL	6
CWI	2
DIFFER	4
GraphenePioneer	1
NXP	1
Radboud Universiteit Nijmegen	15
Rijksuniversiteit Groningen	21
Technische Universiteit Delft	23
Technische Universiteit Eindhoven	13
Universiteit Leiden	16
Universiteit Twente	13
Universiteit Utrecht	14
Universiteit van Amsterdam	17
Vrije Universiteit Amsterdam	3
VSPARTICLE	1
<b>Total</b>	<b>157</b>

# Composition advisory committee

## Nano, Quantum and Material Physics

Beatriz Noheda	RUG
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Nigel Hussey	RU/UT
Harold Zandvliet	UT
Bas van de Meerakker	RU
Gary Steele	TUD
Servaas Kokkelmans	TU/e
Sanli Faez	UU
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Emily Kernen	Photonis