PHYSICS OF MATTER AND WAVES

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The scales of length, time, and energy that are intermediate between the infinitely small and the infinitely large define the world we live in and that we experience. The relevant fundamental forces that act on these scales are, for nearly all phenomena, the gravitational and the electromagnetic forces. This is the subject of Chapter 2 of the EPS Grand Challenges

At the energy scales that characterise our world, the relevant physical approaches take atoms, ions, and electrons as fundamental building blocks of matter, and photons as those of light. The constituents, in the unimaginable vastness of their numbers and the fantastic variety of their possible arrangements, lead to the astounding complexity of our world and the dazzling phenomena it harbours. The world we experience is also the world on which we may intervene. When done in a controlled manner, this intervention – or experiment – belongs to the realm of science and technology. But even when we do not strive to control, our actions are still determined by the physical workings of the world's constituent building blocks and their interactions. When one comes to think of it, an atom itself is a hugely complex system. Mathematics abdicates when faced with the problem of providing an exact description of more than three interacting objects, and all atoms are in this situation: quarks make up hadrons, hadrons make up the atomic nuclei, and nuclei and electrons make up the atom. The internal organisation of the atom is the result of, for most elements, numerous "correlations". The simultaneous presence of several and often many interacting particles lead to the organisation of matter. This is even more true when one assembles atoms into molecules, atoms and molecules into liquids and solids, and liquid and solid components into complex systems. We witness that the forces • • •

▲ **FIG.1:** Interactions and emergence, illustrated by a water drop falling on a water surface. Because of the interaction between water molecules, the small drop has a visible effect over a large range, leading to the emergence of the ripple and the central rebound.

▲ FIG. 2: Manipulation of light. This example illustrates the numerical design of a microscale optical system separating different spectral waves and funnelling them into different waveguides. Adapted from [1] with permission from APS.

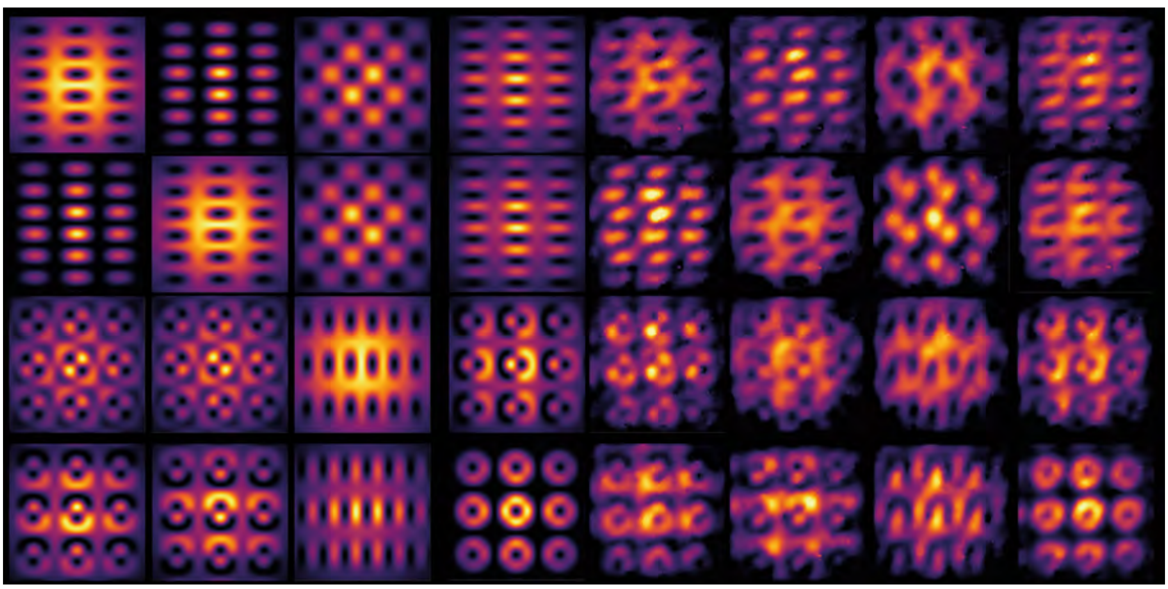
which objects around us exert on each other, and the phenomena that emerge, are the net result of their internal, physical organisation. The myriad particles involved and the manner in which they can interact and can be made to interact vouch for complexity. In chapter 2 of the EPS Grand Challenges work done in the various research fields are presented.

Quantum many-body systems - The study of "Quantum many-body systems and emerging phenomena" is concerned with the organisation of matter and the excitations its constituents can undergo when stimulated by light or other, impinging, particles. It describes how "emergent" behaviour can emerge from the interaction of many constituent particles (see Figure 1 for a parabolic illustration), and how the quantum mechanical nature of our world determines the nature of the objects that constitute it, even though we may not at all be aware of such. It also describes when a quantum description is needed, that is, when the conditions of observation are such that coherent interactions and propagation of light and particles are guaranteed. When the quantum mechanical coherence of light and matter is disturbed in the process at hand, we may resort to what has become known as the "classical description". *Read more: Lucia Reining, Quantum many-body systems and emerging phenomena.*

New materials - In searching for new materials the – even limited - understanding of the organisation of matter helps mankind fashion the materials and tools need to tackle the world's challenges and problems. Here, in principle, there is nothing new. Did not the smithies and rock-hewers of prehistoric and early historic times draw on their experience to fashion stone and metal tools? Now, the formidable scientific progress accumulated over the last two centuries allows for mankind to imagine and make materials according to need, in a sustainable and controlled manner, at all scales down to that of the very constituent atoms. New and urgent challenges are to take into account the availability of material and energetic resources and to design those material assemblies and those processes that are most appropriate for a given application, choosing from the many millions of materials that nature would allow.
Read more: Claudia Draxl and José Maria de Teresa Nogueras, The search for New Materials.

Manipulating atoms and photons - Nowhere does the force of science have an impact as great as when matter and light are manipulated on the smallest of scales – the nanometer (*i.e.* 10^{-9} m) or below. "Manipulating Atoms and photons, photonics and nanophysics" shape today's and tomorrow's technologies and allow us to dive into

▶ FIG. 3: Twisting Light Beams on Demand: Beams of light with phase-structured wave fronts provide a robust, high-dimensional medium for metrology and communication applications (from A.R. Cameron *et al.*, Phys. Rev. A 104, L051701 (2021) © APS



the smallest length scales defining materials and the systems they can constitute and, indeed, back into the quantum realm. The understanding of how interactions between particles manifest themselves differently depending on the length scale we are working on and how the quantum mechanical nature of these interactions can be brought out, allows one to put both to work to define entirely new tools, systems, and paradigms (see *e.g.*, Figure 2).
Read more: Jean-Jacques Greffet, Antoine Browaeys, Frédéric Druon, and Pierre Sénéor, Manipulating photons and atoms: photonics and nanophysics.

Extreme light - What goes for matter also goes for light, and what goes for space also goes for time. Recent and astounding advances now allow one to fashion extremely bright light beams, extremely short light pulses, or a combination of both, giving rise to the realm that has become known as "Extreme Light". Extreme brightness allows us to examine the structure of matter, its organisation, and its response to excitations in the very finest details – for it is those details that most often give away the fundamentals at stake in determining the nature of the studied object in the first place. Ultra-short and bright pulses allow one to make "movies of matter". Much as stroboscopic illumination of moving beings can reveal the gestures in motion, pico- and femto-second illumination of matter unveils the dance of electrons in matter: how matter is excited, how matter reacts, how matter transforms. Extremely spectacular results with high-stake implications in many fields (chemistry, biology, medicine…) are to be expected here. Moreover, being able to intervene at the rhythm of matter itself allows us to reorganise it, yielding yet another tool for the creation of new (quantum) states of matter designed as tools to face the challenges of humankind.
Read more: Franck Lépine, Jan Lüning, Pascal Salières, Luis Oliveira e Silva, Thomas Tschentscher, Antje Vollmer, Extreme Light.

Extended classical systems – In the EPS Grand Challenges, the summary of the Physics of Matter and Waves in the world as we know it and discover it is completed by the description of classical systems with numerous degrees of freedom and the multiplicity of interactions in systems that are not necessarily characterised atomic length and time scales and quantum coherence. This opens the way for the most complex of organisations of matter as we know it: life itself.

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