Editorial

Quantum fluctuations and coherence in optical and atomic structures

From simple interference fringes, over molecular wave packets, to nonlinear optical patterns – the fundamental interaction between light and matter leads to the formation of structures in many areas of atomic and optical physics. Sophisticated technology in experimental quantum optics, as well as modern computational tools available to theorists, have led to spectacular achievements in the investigation of quantum structures.

This special issue is dedicated to recent developments in this area. It presents a selection of examples where quantum dynamics, fluctuations, and coherence generate structures in time or in space or where such structures are observed experimentally. The examples range from coherence phenomena in condensed matter, over atoms in optical structures, entanglement in light and matter, to quantum patterns in nonlinear optics and quantum imaging.

The combination of such seemingly diverse subjects formed the basis of a successful European TMR network, "Quantum Structures" (visit `http://cnqo.phys.strath.ac.uk/~gianluca/QSTRUCT/`). This special issue partly reflects the results and collaborations of the network, going however well beyond its scope by including contributions from a global community and from many related topics which were not addressed directly in the network.

The aim of this issue is to present side by side these different topics, all of which are loosely summarized under quantum structures, to highlight their common aspects, their differences, and the progress which resulted from the mutual exchange of results, methods, and knowledge. To guide the reader, we have organized the articles into subsections which follow a rough division into structures in material systems and structures in optical fields. Nevertheless, in the following introduction we point out connections between the contributions which go beyond these usual criteria, thus highlighting the truly interdisciplinary nature of quantum structures.

Much of the progress in atom optics has been generated by the application of concepts from wave optics to matter waves. An example is the contribution by Franke-Arnold *et al.* The authors investigate the coherence properties of two trapped cold atoms using concepts developed in wave optics. Nevertheless, novel features appear in this system due to the quantum statistics – as atoms may be bosons or fermions – and due to interactions. Matter waves find a spectacular manifestation in Bose-Einstein condensates (BECs) of cold dilute atomic gases. Several concepts of wave optics, like the laser, have been discussed in relation to BECs, and the field of atom optics with BECs is rapidly developing. The similarity between the theoretical description of a weakly interacting BEC with that of a non-linear optical system has motivated a series of experiments that led to the observation of, *e.g.*, solitons, vortices and vortex crystallization in matter waves. In this context, the paper by Josopait *et al.* describes the dynamics of a Bose-Einstein condensate containing a vortex. The vortex stability is discussed as a function of the interparticle interaction, which can be tuned using Feshbach resonances, and the dynamics of the BEC reflected by an atomic mirror is investigated.

Non-linear optics merges with atomic physics also in a relatively new research area which aims at quantum non-linear optics with cold atomic gases. Labeyrie *et al.* use a dense, laser-cooled atomic gas as a non-linear medium for light propagation, and discuss the conditions for observing optical patterns in the transmitted beam.

Pattern formation in non-linear optical media is one of the numerous forms of self-organization that these systems display, including also turbulence and optical solitons. With respects to other physical systems, where these phenomena are commonly observed, optical systems are however special: at optical frequencies thermal fluctuations are negligible and do not hide the presence of quantum fluctuations, even at room temperature. Remarkably, the interplay between non-linearity and quantum noise leads to novel phenomena, including optical patterns driven by quantum noise, quantum images, non-classical spatio-temporal correlations, and spatial quantum entanglement. Quantum images are an example of spatial structures dominated by quantum noise, where the structure is absent at a classical level and only proper correlation functions of quantum fluctuations reveal the presence of a regular spatial order. Hoyuelos *et al.* describe an example of such an image, which is formed in the cross section of the light emitted by an optical parametric oscillator, close to but below the threshold for a square pattern formation. The optical parametric oscillator is also studied in the paper by Rabbiosi *et al.* which describes the onset of a spatial structure consisting of arrays of localized peaks (cavity solitons) in the transverse cross section of the signal beam. This represents an example of a "disorder to order" transition mediated by quantum noise, where the ordered arrays of solitons are selected among the many possible stable states, only thanks to the presence of quantum noise.

As the study of the dynamics of quantum fluctuations in spatially extended systems is a non-traditional subject in quantum optics, alternative techniques of theoretical analysis are needed. The paper by Zambrini *et al.* proposes an approach based on the use of phase-space representations, in particular of the Q–function with its associated nonlinear Langevin equations. This method provides a full description of the transition from a quantum image to a classical structure through a modulation instability. The Q–representation is also used in a different physical system, the dynamics of the electrons in a driven Helium atom, in the paper by Schlagheck and Buchleitner. Here the authors investigate the quantum manifestations of order and disorder in the motion of the electrons, identifying correspondences between features of the classical phase space and the quantum dynamics.

In optical patterns the structure and stability are critically determined by the type of non-linearity of the medium where light propagates, and by the cavity geometry. In atom optics, spatial atomic patterns can be created by light potentials, in particular by arrangements of suitably polarized laser beams which form an optical lattice. The atoms experience mechanical forces arising from the gradient of the light potential. Depending on the tuning of the lasers with respect to the driven atomic transition, these light forces can have a strong or negligible dissipative component, leading to incoherent or coherent motional dynamics. Atomic motion in optical lattices is experimentally investigated in the contributions by Carminati *et al.* and Jersblad *et al.* The first article investigates motion-induced resonances in a three-dimensional optical lattice which are observed through pump-probe laser spectroscopy. The latter contribution studies the effect of the lattice geometry on the atomic steady-state by measuring velocity distributions. The creation of more complex light structures is the subject of the paper by Ellmann *et al.*, where the realization of a double optical lattice is discussed. Such lattices may open up the possibility of coherent manipulation of the atoms in the individual potential wells.

An alternative way to structure atoms spatially is discussed by Grabowski and Pfau: here, a regular arrangement of magnetic and magneto-optical traps for ultracold atoms above a surface is described and experimentally observed, where the lattice configuration is determined by the direction of currents in wire segments beneath the surface. In a different physical systems, semiconductor quantum dots, Jacak *et al.* study the coupling of artificial atoms with the collective excitations of the bulk material in which they are embedded, and investigate coherent and incoherent effects due to this interaction.

The presence of correlations at the quantum level leads naturally to the issue of entanglement. This is an exclusive feature of the quantum world, which represents a valuable resource for quantum information processing and for high-precision measurements. The definition and criteria for measuring entanglement have been traditionally formulated within the Hilbert-space formalism (the quantum state formalism). However, quantum structures are intrinsically multi-mode systems, for which the Hilbert-space approach is often unpractical and cumbersome. More appealing are the "classical looking" phase space descriptions, where it is hence of great importance to reformulate concepts such as entanglement or Bell inequalities. The paper by Santos addresses the general problem of characterizing the entanglement properties of an electromagnetic field in the language of Q–representation. Entanglement involving the spatial modes of the electromagnetic field carrying orbital angular momentum provides new degrees of freedom and could play an important role in the field of quantum information, since such non-classical states enable the possibility of multichannel communications. The paper by Barbosa discusses quantum states of twin photons produced by parametric down-conversion and entangled in polarization and orbital angular momentum.

The issue of entanglement is intrinsically connected to decoherence, and to the transition from the quantum to the classical world. In particular, massive systems are characterized by strong interactions with the environment, and at room temperature they usually exhibit classical behaviour. In this context, the paper by Karlsson discusses the decay of quantum correlations of protons and positive muons in condensed matter, a system characterized by strong coupling to the environment, and proposes experiments where such quantum correlations could be measured. Mancini *et al.* investigate macroscopic manifestations of quantum features, presenting a proposal for entangling the macroscopic oscillation modes of two cavity mirrors by coupling them to an optical cavity mode. This kind of continuous-variable quantum entanglement may find applications in high-precision measurements, like in atomic force microscopy or gravity wave detection. The question of entanglement for high-precision measurements is also addressed by the paper of Yurtsever *et al.* which discusses entanglement between matter waves, and proposes the use of entangled atom pairs for a highly sensitive quantum gravity gradiometer.

Besides their fundamental interest as a manifestation of quantum fluctuations, spatial quantum correlations in optical beams find their most natural and promising applications in the field of image processing and, more in general, of parallel processing of information. This has opened a new chapter of quantum optics that has been given the name "quantum imaging". In this context, one of the first achievements have been the so-called entangled two-photon imaging experiments. This is a technique that exploits the quantum entanglement of a two-photon state to retrieve information about a remote object. In the typical set-up, one photon out of a pair produced by spontaneous parametric down-conversion is used to probe an object, while the other provides a reference. The image of the object emerges in the coincidence counting rate registered as a function of the second photon position. The paper by Shih offers an extensive review of fundamental aspects linked to the entangled two-photon imaging phenomena. It illustrates how quantum imaging techniques may improve classical spatial resolution and presents some of their potential applications for lithography and other microsystem fabrication technologies. A different view on the problem is offered by the paper of Tan *et al.*, which reformulates the two-photon quantum imaging theory from the point of view of retrodictive quantum theory.

Since long, quantum noise has been known to represent a limit in high-precision optical measurements. In this context, the contribution by Eschner discusses a single trapped atom probing an optical field and shows that the quantum noise in the atomic motion poses the ultimate limit to the achievable resolution. Recently, it was recognized that quantum noise affects also our ability to resolve an optical image or to detect a small displacement of an optical beam. Properly synthesized multi-mode quantum states are able to circumvent the quantum noise limit and to improve our resolution capabilities in measuring beam displacements. The paper by Barnett *et al.* shows the similarities between longitudinal phase shifts and transverse beam displacements measurements. Like in interferometry, the sensitivity in the transverse displacement measurement is ultimately limited by the quantum nature of light and can be improved by the use of specific non classical states. The problem of realizing a multi-mode squeezed state is addressed by the paper of Petsas *et al.* It discusses a realistic implementation of parametric down-conversion in a confocal cavity, able to produce a significant amount of squeezing in small portions of the signal beam cross section.

Quantum imaging with macroscopic light beams is a rather new subject of investigation, which represents a non-trivial challenge from the point of view of experimental implementations. One of the main problems is posed by detectors, which should be able to resolve the spatial features of the detected beam with a sensitivity in the photon number measurement beyond the shot noise level. The calibrated CCD camera developed by Jiang *et al.* makes it possible to get rid of electronic noise or spatial inhomogeneities, affecting most of the spatially resolved detectors, and allows the retrieval of spatial shot noise in its full dynamic range.

We hope that this special issue helps stimulating further collaborations and fruitful scientific exchange between and beyond the presented fields.

We would like to thank the authors for their contributions and the referees for their time and their thoroughness. Our sincerest thanks go to Solange Guéhot in the EPJ D editorial office for very efficiently taking care of all administrative matters.

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