Q 34: In Memoriam of Hermann Haken (joint session Q/MO)

Physicist Hermann Haken, who died on August 14, 2024 at the age of 97, made groundbreaking contributions to solid-state physics and quantum optics. As a pioneer of laser theory, he recognized early on the ubiquity of non-equilibrium phase transitions. This led to the foundation of the self-organization theory of synergetics, which has been applied to countless systems of both inanimate and living nature. The Symposium honours his life work and outlines exemplarily how his scientific achievements live on in current quantum optics research.

Time: Wednesday 11:00–13:00 Location: HS I PI

Invited Talk Q 34.1 Wed 11:00 HS I PI

Haken's quantum field theoretical understanding of semiconductors and lasers and its present-day impact — •Cun-Zheng Ning — Shenzhen Technology University, China

Prof. Haken was among the earliest few who applied the then-new quantum field theory (QFT) to understand physical processes in semiconductors in the 1950s and lasers in the 1960s. The first decade of his scientific career was devoted to the QFT treatment of non-metallic solids. His long-lasting impacts are reflected by popular terms such as the Haken Potential for excitons and Feynman-Haken Path Integral for calculating the ground-state energy of polarons. The second decade of his career started at Stuttgart. It was devoted to the newly invented laser whose fundamental understanding, as he quickly realized, required extending the known QFT to include noise and dissipation. In the process, he established the full quantum theory for open systems and laid the foundation for Synergetics. His laser theory not only explained or predicted many phenomena in lasers but also provided a general framework for the understanding of problems whenever light-matter interaction is involved. While his first two decades focused on the QFT treatment of semiconductors or light field respectively, a proper description of semiconductor optics requires the QFT treatment of both semiconductors and optical field self-consistently. This task turns out to be as challenging as it is rewarding when Coulomb interaction is included and remains an active field of research today, continued by generations of his students. This talk will cover aspects of Prof Haken's early contributions and some recent progress.

Invited Talk Q 34.2 Wed 11:30 HS I PI

Bose-Einstein condensation of photons in vertical-cavity surface-emitting lasers — •Maciej Pieczarka — Wrocław University of Science and Technology, Wrocław, Poland

Professor Haken pioneered the development of the quantum theory of lasers and discovered that lasing action can be viewed as a nonequilibrium second-order phase transition. This visionary and broader view inspired many to find a link between lasing and the Bose-Einstein condensation (BEC) of photons. It appears that the worlds of lasers and BEC are deeply intertwined, as BEC was found in dye-filled microcavities [1] and, more recently, in semiconductor lasers [2].

I will present our demonstration of photon BEC phase transition in a real-world device - a Vertical-Cavity Surface-Emitting Laser (VCSEL) [2]. Besides distinctive differences from the complete thermal equilibrium, we show that photons in a VCSEL follow the equation of state for an ideal bosonic gas. We argue that photon BEC can be a much more common phenomenon in laser physics than previously anticipated.

[1] J. Klaers et al., Nature **468**, 545 (2010).
[2] M. Pieczarka et al., Nature Photonics **18**, 1090 (2024).

Invited Talk Q 34.3 Wed 12:00 HS I PI

Photons in a dye-filled cavity: quantum-optical system interpolating between Bose-Einstein condensates and laser-like states — •Milan Radonjić — Universität Hamburg, Germany — University of Belgrade, Serbia

It is well known that photons in a dye-filled cavity exhibit a Bose-Einstein condensate (BEC) of light [1]. We generalize the microscopic non-equilibrium Kirton-Keeling model [2] of such a system by carefully considering the interplay of coherent and dissipative dynamics within the Lindblad master equation framework pioneered by Hermann Haken in his theory of lasers [3]. The resulting equations of motion of both photonic and matter degrees of freedom are then used to study the steady-state properties of the system. We demonstrate that this system can interpolate between photon BEC and laser-like states, depending on whether the dissipative or coherent influence of the environment is dominant [4]. In the former case, we show that the cavity modes of different energies are essentially uncorrelated. In the laser-like regime, some cavity mode acquires macroscopic occupation, while the populations of other cavity levels strongly deviate from the Bose-Einstein distribution. Additionally, the steady state contains a rather high degree of correlations between the different cavity modes.

[1] J. Klaers et al., Nature **468**, 545 (2010).
[2] P. Kirton and J. Keeling, Phys. Rev. Lett. **111**, 100404 (2013).
[1] H. Haken, Laser Theory, Springer (1970, 1984).
[4] M. Radonjić et al., New J. Phys. **20**, 055014 (2018).

Invited Talk Q 34.4 Wed 12:30 HS I PI

From laser physics to nonlinear dynamics and synergetics — •Eckehard Schöll — TU Berlin, Germany

Hermann Haken was a pioneer of laser physics and developed the first full quantum theory of the laser [1]. He interpreted the laser transition as a nonequilibrium phase transition [2], and found that this is a special case of a much wider class of open systems driven far from thermodynamic equilibrium. Based upon this observation he founded the field of synergetics which deals with systems composed of many subsystems like atoms, molecules, photons, cells, etc., and shows that cooperation of the subsystems leads to spatial, temporal, or functional structures by self-organization [3]. He demonstrated that the semiclassical laser equations are mathematically equivalent to the Lorenz equation derived from fluid dynamics [4], exhibiting higher instabilities and chaos, like many other nonlinear dynamical systems in physics, chemistry, biology, medicine, and even economics, sociology and psychology. This has given rise to a plethora of new phenomena in nonequilibrium system widely studied during the past five decades. Coherence resonance is just one example which was first discovered by Haken [5], and later studied in various systems ranging from lasers to the brain.

[1] H. Haken, Laser Theory, Springer (1970, 1984).
[2] R. Graham and H. Haken, Z. Phys. **237**, 31 (1970).
[3] H. Haken, Synergetics, An Introduction, Springer (1977).
[4] H. Haken, Phys. Lett. **53A**, 77 (1975).
[5] G. Hu et al., Phys. Rev. Lett. **71**, 807 (1993).