Microscopic Structured Light-Matter Coupling for Atomic and Molecular Quantum Control

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Optical tweezers and tightly focused beams are now central tools in atomic and molecular quantum science, but many current platforms operate in regimes where plane-wave, paraxial, and point-particle approximations are no longer sufficient. In this talk, I will outline how our previous work on structured light-matter interaction provides the technical basis for a research program that treats the microscopic structure of optical fields as a genuine control resource, rather than as a hidden experimental detail.

The first part of the program focuses on atoms and molecules in realistic high-numerical-aperture tweezer fields. Longitudinal field components, polarization gradients, tensor light shifts, and spatial phase structure can generate internal-motion entanglement, decoherence, leakage, and heating. A predictive microscopic theory is therefore needed to identify dominant error channels and design mitigation strategies. For molecules, the rotational degree of freedom amplifies these effects, but also opens new possibilities for rotational control and engineered dipolar interactions. The second part applies these ideas to the trap-resolved assembly of microwave-dressed molecular complexes. Here, structured optical confinement and microwave-induced interactions define light-induced potential energy surfaces for coherent dimer and trimer formation. I will discuss how wavepacket methods, especially multilayer MCTDH, can be used to model and optimize these processes, and why Heidelberg provides an ideal environment for developing this direction.