CUI: Functionalities of Rydberg Matter (FORM2025)

Titles and Abstracts for the conference

May 5th: 14:00 to 17:00

1) **Dr. Nina Stiesdal**, University of Bonn

Title: Magic wavelength traps for collective Rydberg excitations

Abstract: Strong, long-range interaction between Rydberg atoms plays an important role in many emerging fields of research, including the field of quantum optics, where the strong interactions are mapped onto photons that are propagating through or stored in the atomic medium as coherent atomic excitations. However, the coherence times of collective atomic excitations are limited by various mechanisms, including thermal atomic motion and inhomogeneous differential light shifts between atoms sharing the coherence. The latter can be suppressed by magic trapping which equalizes the AC Stark shifts for the ground and excited levels of the atom.

In this talk, I present our implementation of a magic trap for ultracold Rydberg atoms. We conduct photon storage and retrieval measurements using two different trapping geometries: an optical lattice and a running wave trap. Our experiments demonstrate that the optimal trap wavelength where the coherence time of the stored excitation is maximized differs for the two geometries. This difference arises from the Rydberg electron wavefunction extending over a significant region of the trapping potential and contributing a ponderomotive part to the total trapping potential on the atom in the Rydberg state. This ponderomotive contribution depends on both the longitudinal standing wave and the radial trap shape. We investigate how this part scales with principle quantum number n, and determine the optimal magic lattice wavelength for different Rydberg states.

2) **Iason Tsiamis**, FU-Berlin

Title: Quantum Control with Rydberg Atoms: Quantum Gates and CW Transistors

Abstract: Rydberg atoms enable both coherent quantum control and nonlinear photonic interactions, forming a versatile platform for quantum technologies. I present two complementary implementations: (1) microwave-dressed trapping potentials on an atom chip enable stable confinement of Rydberg qubits and long-range SWAP gates via a planar microwave resonator; (2) in a separate setup, continuous-wave quantum transistor devices based on Rydberg ensembles exploit single-photon-induced breakdown of electromagnetically induced transparency to modulate a probe field. These results demonstrate how engineered Rydberg interactions support both gate-based quantum processing and continuous, single-photon-level photonic control.

3) **Dr. Simon Balthasar Jaeger**, University of Bonn

Title: Effective Lindblad master equations for atoms coupled to dissipative bosonic modes

Abstract: We develop atom-only Lindblad master equations for the description of atoms that couple with and via dissipative bosonic modes. We employ a Schrieffer-Wolff transformation to decouple the bosonic from the atomic degrees of freedom in the parameter regime where the decay of the bosonic degrees is much faster than the typical relaxation time of the atoms. In this regime we derive the transformation which includes the most relevant retardation effects between the bosonic and the atomic degrees of freedom. After the application of this transformation, the effective Lindblad master equation is obtained by tracing over the bosonic degrees of freedom and captures the atomic interactions and dissipation mediated by the bosons. We use this approach to derive Lindblad master equations which can describe the phase transitions, steady states, and dynamics in the dissipative Dicke model. In addition, we show that such master equations can be used in presence of resonant periodic driving and predict the formation and stabilization of dissipative Dicke time crystals. We also discuss how to extend the theory to describe systems with continuous symmetries where descriptions with the Redfield master equation fail. Our work provides general methods for the efficient theoretical description of retarded boson-mediated interactions and dissipation.

4) **Milena Simić**, MPIPKS Dresden

Title: Permanent Dipole Moments in Long-range Rydberg Molecules

Abstract: Despite being homonuclear, long-range Rydberg molecules posses permanent dipole moments. These range from a few Debye of low l-states to a few kDebye of the trilobite state. The latter was theoretically predicted when the long-range Rydberg molecules were proposed, while the permanent dipole moments of low l-states came to be known a decade later, together with an experimental proof. In order to describe the existence of these dipole moments, a simple perturbative method was developed. However, ever since there has not been a more detailed study on the conditions when this perturbative method can be used, what contributes to the dipole moments and how numerically stable these calculations are. With our recent study we are filling in the missing gap on permanent dipole moments of s-states.

5) **Aileen Durst**, MPIPKS Dresden

Title: Rydberg Impurities in Bose-Einstein Condensates

Abstract: Highly electronically excited atomic impurities within a BEC typically have interactions characterised by a scattering length that may rival or even surpass the average spacing between the surrounding bosons. The significance of these interactions depends on the thermal de Broglie wavelength; for shorter lengths, the system exhibits a rich absorption spectrum which extends typical polaron physics. However, within a dense bath, the absorption spectrum consists only of a broad single Gaussian, indicating an almost classical behaviour.

Beyond altering interaction ranges, scattering length and interaction strength, the electronic angular states of the impurity can be manipulated, breaking the spherical symmetry of the interactions. In free space, this manipulation leads to the emergence of $l(l+1)$ degenerate electronic potential energy surfaces, introducing non-additive interactions. Our investigation delves into the impact of these anisotropic and non-additive interactions on the absorption spectrum of a Rydberg impurity within an ideal BEC.

May 6th: 9:00 to 17:00

6) **Dr. Moritz Berngruber**, University of Stuttgart

Title: Direct observation of ion-Rydberg atom interactions using a high-resolution ion microscope

Abstract: By using a high-resolution ion microscope we can image ion and Rydberg systems with a spatial resolution of at least 200nm and a temporal resolution of less than 50ns. This allows to study various dynamic processes that arise from Rydberg-ion interactions.
On the one hand, we can observe systems consisting of one ion and one Rydberg atom that interact attractively, leading to an ion-Rydberg collision. Due to the complex level structure of the Rydberg atom in the electric field of the ion, the collision can happen on a multitude of different collision channels, which take place on different time scales. On the other hand, we can also experimentally observe how a Rydberg atom binds to an ion and forms a ultralong-range Rydberg molecule.
Furthermore, will also present some preliminary theoretical results, which support the existence of bound Rydberg-Ion-Rydberg trimers that exhibit a non-trivial azimuthal structure.

7) **Markus Exner**, RPTU Kaiserslautern

Title: High precision spectroscopy of trilobite Rydberg molecules

Abstract: This talk summarizes our recent progress in the study of trilobite Rydberg molecules. A three-photon excitation scheme enabled the creation of pure trilobite molecules, revealing multiple vibrational states with large dipole moments, near-harmonic behavior, and extended lifetimes due to their predominant high-angular-momentum character. A second work presents a comprehensive spectroscopic study of trilobite Rydberg molecules, offering remarkable insights into their electron-atom interactions. High-precision vibrational series for different principal quantum numbers (n = 22 to 27) were measured with a realtive spectroscopic resolution of 10^{-4}. Using a Green's function approach including all relevant spin interactions, the observed spectrum is successfully reproduced, enabling the extraction of the low-energy triplet S-wave scattering phase shift with unprecedented precision. The most recent research reveals highly excited vibrational states (v ≈ 100) stabilized by non-adiabatic coupling, thus marking the first direct observation of beyond-Born-Oppenheimer effects in these molecules. This stabilization is predicted to occur only for certain Rydberg levels where the avoided crossing between trilobite butterfly potential energy curves nearly vanishes.

8) **Neethu Abraham**, MPIPKS Dresden

Title: Non-adiabatic Coupling in Charged Rydberg Molecules: The Delicate Balance Between Stability and Decay

Abstract: The creation and study of exotic Rydberg molecules including Rydberg macrodimers and Rydberg atom-ion systems has significantly advanced our understanding of long-range interactions in ultracold environments. Unlike bare Rydberg atoms, these molecular systems often exhibit reduced lifetimes, suggesting a key role played by non-radiative decay mechanisms. One such process is non-adiabatic coupling between electronic potential energy curves, which can enable vibrational bound states to transition onto repulsive curves and subsequently decay. We explore this mechanism using a streamlined multichannel R-matrix method to identify resonance

positions and widths and highlight how interchannel coupling modifies stability. Additionally, I will outline our ongoing efforts to gain a semiclassical understanding of this decay process using a WKB-based approach, which we expect to offer analytical insight into the interference effects observed in our numerical calculations.

9) **Dr. Giacomo Giudice**, PLANQC, Garching

Title: Fast entangling gates for Rydberg atoms via resonant dipole-dipole interaction

Abstract: The advent of digital neutral-atom quantum computers relies on the development of fast and robust protocols for high-fidelity quantum operations. In this talk, I will briefly review the current state-of-the-art in entangling gate schemes and introduce a new protocol that leverages resonant dipole-dipole interactions between Rydberg states. This protocol uses a ground-state qubit and two Rydberg levels per atom: a laser field excites atoms to one of the Rydberg states, while a microwave field couples the two Rydberg levels. This all-microwave-driven approach eliminates the need for optical amplitude and phase control and offers significant advantages over conventional van der Waals-based gates, including faster gate times and reduced sensitivity to Rydberg-state decay. Moreover, the protocol can be systematically stabilized against interatomic distance fluctuations and is suitable for realistic experimental setups. These results highlight the potential of microwave-driven dipolar interactions as a powerful tool for quantum computation with neutral atoms.

10) **Dr. Sebastian Weber**, University of Stuttgart

Title: Designing Rydberg Quantum Gates

Abstract: The neutral-atom platform offers entangling gates via the Rydberg blockade. In this talk, I present an optimal protocol for realizing controlled-phase gates for arbitrary phases. Our proposed protocol is time-optimal and requires only a minimum amount of tunability. Using the example of Hamiltonian simulations, I show that our gate protocol can improve the overall fidelity of Trotterized quantum circuits, pushing NISQ-era Rydberg quantum computers closer to quantum advantage. With the aim of being close to experiments, I discuss how cross-talk from local addressing can be suppressed. Moreover, I show how Rydberg states can be found that are suitable for high-fidelity gates, using the new version of our open-source software “pairinteraction."

11) **Dr. Titus Franz**, MPQ Garching

Title: Simulating Chemistry with Fermionic Optical Superlattices

Abstract: We show that quantum number preserving Ansätze for variational optimization in quantum chemistry find an elegant mapping to ultracold fermions in optical superlattices. Using native Hubbard dynamics, trial ground states of molecular Hamiltonians can be prepared and their molecular energies measured in the lattice. The scheme requires local control over interactions and chemical potentials and global control over tunneling dynamics, but foregoes the need for optical tweezers, shuttling operations, or long-range interactions. We describe a complete compilation pipeline from the molecular Hamiltonian to the sequence of lattice operations, thus providing a concrete link between quantum simulation and chemistry. Our work enables the application of recent quantum algorithmic techniques, such as Double Factorization and quantum Tailored Coupled Cluster, to present-day fermionic optical lattice systems with significant improvements in the required number of experimental repetitions. We provide detailed quantum resource estimates for small non-trivial hardware experiments

12) **Dr. Pascal Weckesser**, MPQ Garching

Title: A Single Rydberg-Atom-Controlled Optical Mirror Based on Subwavelength Atomic Arrays

Abstract: Controlling light–matter interactions is at the heart of many quantum science applications. A promising new approach leverages photon-mediated dipole-dipole interactions in structured, subwavelength arrays of quantum emitters to manipulate optical responses in fundamentally novel ways. This talk demonstrates active control of such an atomic mirror using a single ancilla atom excited to a Rydberg state. By admixing Rydberg character into the atomic array and harnessing strong dipolar interactions with the ancilla, we achieve switching of the mirror's optical response. Coherent Rabi oscillations of the ancilla atom enable precise tuning of the system's transmission and reflection properties. Furthermore, by increasing the size of the atomic mirror, we spatially resolve the effective interaction region around the ancilla atom. Our results open new avenues for realizing tunable quantum metasurfaces and enable controlled atom–photon entanglement.

13) **Kapil Goswami**, University of Hamburg

Title: tba

Abstract: tba

14) **Achim Scholz**, University of Stuttgart

Title: Towards Local Single- and Two-Qubit Control in a Neutral Atom Quantum Computer

Abstract: The QRydDemo project aims to realize a Rydberg atom quantum computer based on the novel fine-structure qubit in strontium. This qubit offers fast single-qubit gates via strong two-photon Raman transitions and, by exploiting a single-photon Rydberg transition, two-qubit gates on the same timescale. Our experimental platform combines a dynamic tweezer architecture with fast optical addressing units, allowing for local control on the full array. To demonstrate coherent control of the novel fine-structure qubit, we show Rabi oscillations for single atoms paving the way for high-fidelity single-qubit gates. Using Ramsey spectroscopy we extract the qubit coherence time and investigate magic trapping conditions for the qubit by tuning the tensor polarizability via an external magnetic field. Towards the realization of high-fidelity two-qubit gate operations we investigate Rydberg state spectroscopy and Rabi oscillations, for which we initialize the fine-structure qubit using a three-photon Raman Transfer.

May 7th: 9:00 to 12:00

15) **Dr. Gerhard Zürn**, University of Heidelberg

Title: Observation of hysteresis in a disordered Heisenberg quantum spin system

Abstract: Disorder plays an important role for the dynamics and the equilibrium properties of complex quantum systems. A paradigmatic model for exploring disordered and frustrated quantum spin systems are quantum spin glasses. Classical spin glasses are typically characterised by a temperature-dependent splitting between two different susceptibilities, which are referred to as zero-field cooled (ZFC) and field-cooled (FC). However, these cannot be measured directly in an isolated quantum system as they involve tuning of the temperature of an external bath coupled to the system. In this presentation we introduce analogues of these susceptibility measurements, tailored for isolated quantum spin systems. We denote them as zero-field annealing (ZFA) and field annealing (FA). We implement these protocols on a Rydberg atom quantum simulator to probe the phase structure of a dipolar-interacting Heisenberg spin model as a function of both energy and disorder. We observe a significant splitting between ZFA and FA susceptibilities in the strongly disordered regime at low energies, indicating multiple equilibrium states. This raises questions about the nature of this regime and its potential connection to a spin glass phase. Generally, the ZFA and FA protocols provide a novel framework for exploring energy-dependent equilibrium properties and hysteresis in isolated quantum many-body systems.

16) **Chris Nill**, University of Tübingen

Title: Resonant Stroboscopic Rydberg Dressing: Electron-Motion Coupling and Multi-Body Interactions

Abstract: Rydberg dressing traditionally refers to a technique where interactions between cold atoms are imprinted through the far off-resonant continuous-wave excitation of high-lying Rydberg states. Dipolar interactions between these electronic states are then translated into effective interactions among ground state atoms. Motivated by recent experiments, we investigate two dressing protocols, in which Rydberg atoms are resonantly excited in a stroboscopic fashion. The first one is non-adiabatic, meaning Rydberg states are excited by short pulses. In this case, mechanical forces among Rydberg atoms result in electron-motion coupling, which generates effective multi-body interactions. In the second, adiabatic protocol, Rydberg states are excited by smoothly varying laser pulses. We show that also in this protocol, substantial multi-body interactions emerge.

17) **Eran Reches**, MPQ Garching

Title: Towards quantum simulation and computation with Sr atom arrays

Abstract: Neutral atom arrays are by now leading platforms for digital quantum simulation and computation, offering an unprecedented degree of control over the individual constituents. In this talk, I will present our implementation of physical qubits based on the Sr-88 clock transition. We have demonstrated high-fidelity detection, single- and two-qubit (Rydberg-based) operations as well as state-of-the-art vacuum-limited lifetime in a non-cryogenic platform. Additionally, I will discuss our ongoing efforts towards local control and the realization of massively-parallel atom moves, setting the stage for future implementations of brickwall-type digital circuits.

18) **Dr. Aslam Parvej,** University of Hamburg

Title: Lamb-Dicke Dynamics of Rydberg Atoms in Optical Tweezers

Abstract: Neutral Rydberg atoms trapped in optical tweezer arrays provide a platform for quantum simulation and computation. In this study, we investigate the dynamics of the Lamb-Dicke-coupled internal states of the atoms, which form the logical qubits, in conjunction with the motion of the optical tweezers across different parameter regimes. In this setup, the logical qubit is coupled to a laser with a Rabi frequency, while each atom is also harmonically trapped with a trap frequency. The impact of coherent motion of the optical tweezers on collective non-equilibrium dynamics of the Rydberg atom is explored for varying Lamb-Dicke parameters and resonant Rabi frequencies.

19) **Lia Kley,** University of Hamburg

Title: Optimal recoil-free state preparation protocols in an optical atom tweezer

Abstract: Quantum computing in atom tweezers requires high-fidelity implementations of quantum operations. Here, we demonstrate the optimal implementation of the transition $|0\rangle \rightarrow |1\rangle$ of two levels, serving as a qubit, of an atom in a tweezer potential, driven by a single-photon Rabi pulse. The Rabi pulse generates a photon recoil of the atom, due to the Lamb-Dicke coupling between the internal and motional degree of freedom, driving the system out of the logical subspace. This detrimental effect is strongly suppressed in the protocols that we propose. Using pulse engineering, we generate optimal protocols composed of a Rabi protocol and a force protocol, corresponding to dynamically displacing the tweezer. We generate these for a large parameter space, from small to large values of the Rabi frequency, and a range of pulse lengths. We identify three main regimes for the optimal protocols, and discuss their properties. In all of these regimes, we demonstrate infidelity well below the current technological standard, thus mitigating a universal challenge in atom tweezers and other quantum technology platforms.