1. Publishable summary

Nanodesigning of Atomic and MolEcular QUAntum Matter *(NAME-QUAM)*

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The NAMEQUAM Project investigates ultracold atom/molecule quantum matter technology for quantum information computational tasks. Parallel quantum processing in periodic nanostructures is expected to lead to significant advances in different areas of quantum information. The research efforts concentrate on atoms/molecules confined in periodic nanostructures, either externally imposed by optical lattices, or self-generated by atomic/molecular interactions. The Project aims at developing novel techniques for quantum engineering and quantum control of ultracold atoms and molecules confined in the periodic nanostructures. An innovative aspect is the development of appropriate tools for achieving quantum control of strongly correlated many body systems at the nanoscale by exploiting moderate- and long-range quantum mechanical interactions. Strongly correlated interacting systems offer a level of computational power that cannot be reached with traditional qubits based on spin, or hyperfine atomic states. Moderate and long, range interactions will be exploited in few body quantum systems in order to produce fast quantum gates using novel robust qubit, and/or qudit, concepts and using quantum states with topological order, all of them highly relevant for next generation quantum information implementations.

The objectives rely on the nanodesign of atomic/molecular quantum matter at the mesoscopic scale of few-body systems. Generation and detection of multiparticle quantum entanglement, robusteness of non-traditional qubits, quantum memories characterise the investigations. The Project will implement new quantum information technologies by achieving the following breakthroughs: characterizing long range interacting systems for optimal quantum information; realizing individual manipulation integrated in proper algorithms; designing new protected qubits or quantum information processors based on long range interactions; developing techniques for topological quantum computation; creating multi-particle entanglement for quantum simulation investigations. As far as the visionary aspects are concerned, the technological and conceptual advances resulting from the planned investigations on multi-particle entanglement, topological structures and nano-optical engineering may lead to the identification of new directions and alternative approaches

towards scalable and miniaturisable quantum information processing.

While the flexible features of the ultracold atom optical lattice quantum technologies are unique, other quantum information communities are catching up with few NAME-QUAM objectives. A persistent and long-term commitment to emerging applications and the transition towards a knowledge-based high-technology industry may be originated is the NAME-QUAM tools can be combined to chip technologies and the quantum hybrid structures.

Few major breakthroughs of the overall Project are listed in the following.

Fig. 1 "Dirac Action" Cover of 15th March 2012 Nature issue, with the following presentation: "The electronic structure of certain solids causes them to exhibit 'Dirac points', which lie at the heart of many fascinating phenomena in condensed-matter physics. In graphene, for example, they cause electrons to act as massless Dirac fermions, able to travel at the speed of light. Two very different methods for controlling the properties of Dirac fermions are presented in this issue of *Nature*. In conventional solids, the electronic structure of the material cannot be varied, so it is difficult to see how the properties of Dirac fermions could be controlled. To avoid this constraint, Tarruell *et al*. create a tunable system of ultracold quantum gases within an adjustable honeycomb optical lattice. This model simulates condensed-matter physics, with atoms in the role of electrons. The Dirac points can be moved and merged to explore the physics of exotic materials such as topological insulators and graphene. On the cover, the band structure of artificial graphene with intersections at two Dirac points."

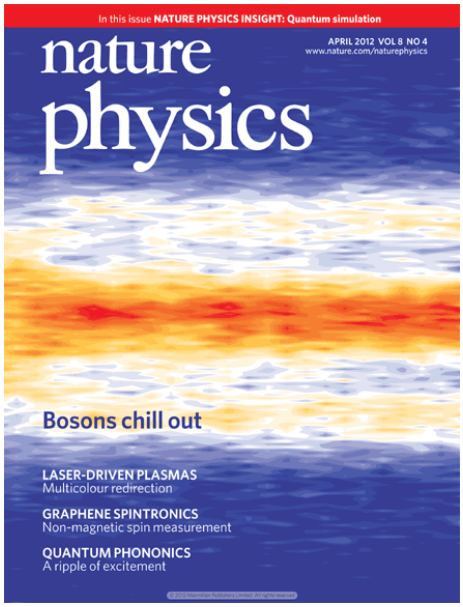


Fig. 2 "Bosons Chill out" Cover of 1th April 2012 Nature Physics issue, with the following presentation: "How quantum many-body systems relax from an initial non-equilibrium state is one of the outstanding problems in quantum statistical physics. A study combining an experimental approach for monitoring the dynamics of strongly correlated cold atoms with theoretical analysis now provides quantitative insight."

ETHZ has developed a tunable two-dimensional optical lattice that can be continuously adjusted to create square, triangular, dimer and honeycomb structures. In the honeycomb lattice, Dirac points were created; these are points where two energy bands intersect linearly, as for example also in graphene[3]. The high degree of control over the lattice parameters provided the means for tuning a number of properties of the Dirac points, including the effective masses of the Dirac fermions and the position of the Dirac points within the Brillouin zone, to a point where two Dirac points merge and annihilate each other, as presented in the Nature cover reported in Fig. 1. These results highlight the great potential that ultracold gases in optical lattices have as a platform for quantum simulations, in particular in situations where the topology of the band structure has an important role. Production

[3] L. Tarruell, D. Greif, T. Uehlinger, G. Jotzu and T. Esslinger, *Creating, moving and merging Dirac points with a Fermi gas in a tunable honeycomb lattice, Nature* **483**, 302–305 (2012).

of topologically ordered states in optical superlattices opens the road to their use in quantum computation applications.

MPG has applied the parallel readout method for a final state analysis to probe the relaxation dynamics of a one-dimensional bosonic density wave[4] has been demon [Trotzky2012]. With OSL, a BEC is loaded into Bose-Hubbard chains with each second lattice site occupied. Furthermore, using the OSL, MPG has developed a new method to read-out in parallel from all sites quasi-local densities, currents and correlations, which probe the non-equilibrium dynamics emerging after rapidly switching on the tunnel coupling along the chain. A rapid relaxation of all these quantities to steady-state values compatible with those of a maximum entropy state is observed. On short timescales, parameter-free time-dependent DMRG numerical simulations could track the many-body dynamics and therefore benchmark the experimental quantum simulation. For long evolution times, however, these classical methods have to fail for the concomitant entanglement growth rendering a classical description infeasible. The experiment, on the other hand, tracks the evolution well beyond the time scale of theoretical predictions. This demonstrates that this system of ultra-cold atoms can be used as an efficient dynamical simulator for relaxation physics in many-body systems. The published paper was selected as a cover of Nature Physics as shown in Fig.2.

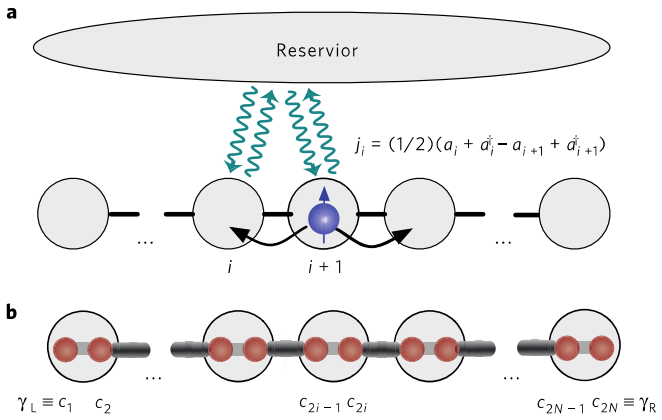


Fig. 3 Set-up for a dissipative Majorana quantum wire. **a,** A reservoir represents a source and drain for the quantum wire, which is coherent over each pair of sites. Independent of the initial condition, the bulk of the system is then cooled into a p-wave superfluid state by dissipatively establishing a pairing link for each two adjacent sites. **b,** Illustration of the stationary state, where in the Majorana basis of real fermions each physical site is split into two Majorana sites. In the bulk all Majorana modes from neighboring sites are paired (black links). For a finite wire two dissipative unpaired Majorana modes appear at the edge as a highly non-local de-coherence-free subspace. They are isolated from the bulk by a dissipative gap.

UIBK has demonstrated that robust edge states and non-Abelian excitations are the trademark of topological states of matter, with promising applications such as "topologically protected" quantum memory and computing[5]. While so far topological phases have been exclusively discussed in a Hamiltonian context, we show that such phases and the associated topological protection and phenomena also emerge in open quantum systems with engineered dissipation. The specific system studied here is a quantum wire of spin-less atomic fermions in an optical lattice coupled to a bath, as schematized in Fig. 3. The key feature of the dissipative dynamics described by a Lindblad master equation is the existence of Majorana edge modes, representing a non-local de-coherence free subspace. The isolation of the edge states is enforced by a dissipative gap in the p-wave paired bulk of the wire. UIBK describes dissipative non-Abelian braiding operations within the Majorana subspace, and UIBK illustrates the insensitivity to imperfections. Topological protection is granted by a nontrivial winding number of the system density matrix.

The polar molecules having large dipole moments represent a very flexible tool for the application of the long-range interactions to the quantum computation. However the quantum control of molecular states is not well developed as that for the atomic ones. Then the collisions between molecules and atoms may represents the handle towards the molecular control. UIBK has examined[6] the laser dressed dipolar and Van der Waals interactions between atoms and polar molecules, when a cold atomic gas with laser admixed Rydberg levels acts as a designed reservoir for both elastic and inelastic collisional molecular processes, as schematized in Fig. 1. The elastic scattering channel is characterized by large elastic scattering cross sections and repulsive shields to protect from close encounter collisions. In addition, UIBK has investigated a dissipative (inelastic) collision where a spontaneously emitted photon carries away (kinetic) energy of the collision partners, thus

[4] S. Trotzky, Y.-A. Chen, A. Flesch, I. P. McCulloch, U. Schollwöck, J. Eisert and I. Bloch, *Probing the relaxation towards equilibrium in an isolated strongly correlated 1D Bose gas*, Nature Physics, **8**, 325 (2012).

[5] S. Diehl, E. Rico Ortega, M. Baranov, P. Zoller, *Topology by Dissipation in Atomic Quantum Wires*, Nature Physics 7, 971 (2011)

[6] Bo Zhao, Alexander Glätzle, Guido Pupillo, P. Zoller, *Atomic Rydberg Reservoirs for Polar Molecules*, arXiv:1112.4170, Phys. Rev. Lett. in press

providing a significant energy loss in a single collision. This leads to the scenario of rapid thermalization and cooling of a molecule in the mili-Kelvin down to the micro-Kelvin regime by cold atoms. UIBK has discussed a scenario where a molecule scatters successively from cold (stationary) atoms in designed elastic and inelastic processes. In this situation reminiscent of a "microscopic version of a pin- ball machine", inelastic scattering events are associated with the emission of a photon implying a "collisional Sisyphus" cooling. While UIBK focused on the simplest possible setup based on Van der Waals interactions, variants based on, e.g. dipole-dipole interactions and low dimensional trapping geometries seem possible.

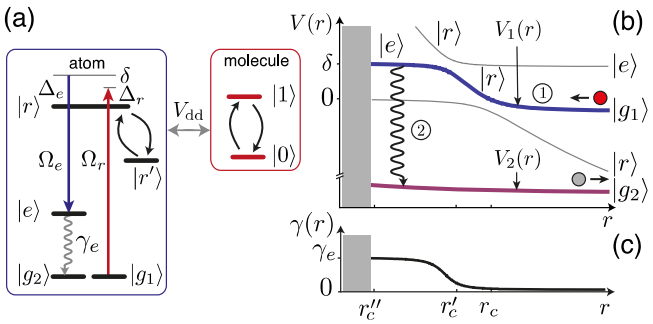
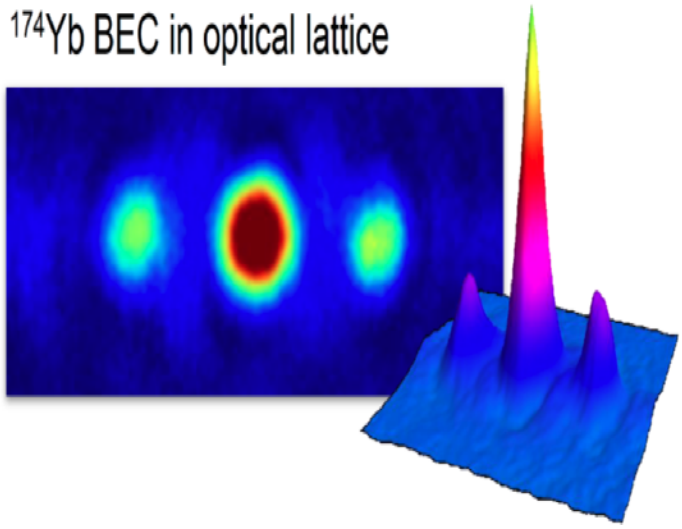


Fig. 4 (a) Energy levels of a laser excited atom and a rotational spectrum of a polar molecule. The Rydberg state interacts with the molecule via a dipole-dipole interaction. (b) Born-Oppenheimer (BO) potentials for the laser dressed atom + molecule complex. We consider a dissipative collision, where (1) the particles collide on the potential curve $V_1(r)$ with the atom in g_1, climb the "blue shield" step at the r_c collisional distance, and (2) are quenched to the potential $V_2(r)$ with atom in g_2. The dominant atomic state is indicated with the molecule in its ground state. (c) Decay rate of the BO potent



LENS loaded a condensed Yb Bose-Einstein condensate into an optical lattice, as shown in the atomic diffraction pattern presented here on the left.

Magnetism plays a key role in modern technology and stimulates research in several branches of condensed matter physics. Although the theory of classical magnetism is well developed, the demonstration of a widely tunable experimental system has remained an elusive goal. A collaboration between ICFO and an experimental group at Hamburg presented the realization of a large-scale simulator for classical magnetism on a triangular lattice by exploiting the particular properties of a quantum system[7]. By using the motional degrees of freedom of atoms trapped in an optical lattice, those authors simulate a large variety of magnetic phases: ferromagnetic, antiferromagnetic, and even frustrated spin configurations. A rich phase diagram is revealed with different types of phase transitions. These results provide a route to study highly debated phases like spin-liquids as well as the dynamics of quantum phase transitions.

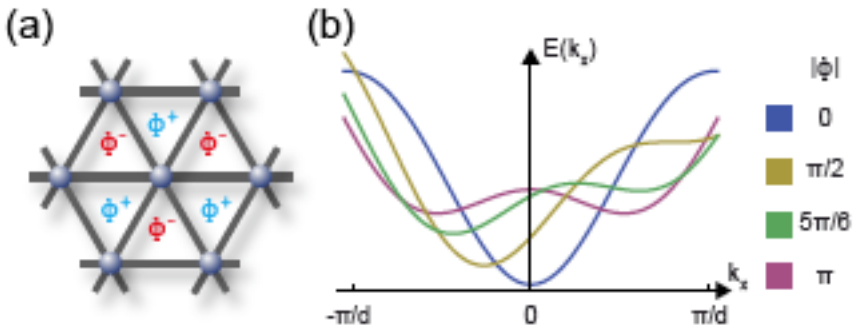


Fig. 5 Creation of magnetic fluxes in triangular lattices. (a) Staggered magnetic fluxes obtained in a 2D triangular lattice. (b) Dispersion relation for different values of the magnetic flux through a plaquette.

[7] J. Struck, C. Ölschläger, M. Weinberg, P. Hauke, J. Simonet, A. Eckardt, M. Lewenstein, K. Sengstock, and P. Windpassinger, Tunable Gauge Potential for Neutral and Spinless Particles in Driven Optical Lattices, Phys. Rev. Lett. **108**, 225304 (2012)