

AFRL-AFOSR-UK-TR-2011-0041



Multiparticle Entanglement and Spatial Addressability of Ultracold Atoms in Optical Lattices

**Immanuel F. Bloch
Stefan Kuhr**

**Johannes Gutenberg-University Mainz
Institute fuer Physik/Quantum
Mainz, Germany 55099**

EOARD GRANT 07-3090

February 2009

Final Report for 1 September 2007 to 31 August 2008

Distribution Statement A: Approved for public release distribution is unlimited.

**Air Force Research Laboratory
Air Force Office of Scientific Research
European Office of Aerospace Research and Development
Unit 4515 Box 14, APO AE 09421**

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY) 17-02-2009	2. REPORT TYPE Final Report	3. DATES COVERED (From – To) 1 September 2007 – 31 August 2008
--	---------------------------------------	--

4. TITLE AND SUBTITLE Multiparticle Entanglement and Spatial Addressability of Ultracold Atoms in Optical Lattices	5a. CONTRACT NUMBER FA8655-07-1-3090
	5b. GRANT NUMBER Grant 07-3090
	5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S) Immanuel F. Bloch Stefan Kuhr	5d. PROJECT NUMBER
	5d. TASK NUMBER
	5e. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Johannes Gutenberg University Mainz Institute fuer Physik/Quantum Mainz, Germany 55099	8. PERFORMING ORGANIZATION REPORT NUMBER N/A
---	--

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) EOARD Unit 4515 BOX 14 APO AE 09421	10. SPONSOR/MONITOR'S ACRONYM(S) AFRL/AFOSR/RSW (EOARD)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-AFOSR-UK-TR-2011-0041

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

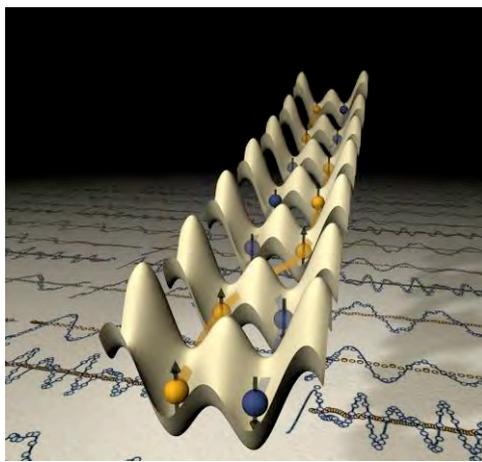
13. SUPPLEMENTARY NOTES

14. ABSTRACT
This report results from a contract tasking Ludwig-Maximilian University of Munich as follows: In this new grant proposal, we specifically try to address important questions that have emerged out of our previous work and that should provide major advances for the field of quantum state engineering and quantum simulations, as well as quantum information processing. Possible applications also include non-classical matter wave field states that are especially useful for improving the performance of matter wave based atom interferometers. The grant proposal will be focused on research to be carried out on an existing and a completely novel experimental apparatus, focusing on two fundamental topics:
1. Generation of robust multi-particle entanglement in optical lattices, with low decoherence rates as a resource for quantum information processing and improved atom interferometers.
2. The construction of a novel experimental apparatus with the possibility to address, observe and manipulate single atoms on single sites of an optical lattice. Based on our experience with previous experiments, we find these two topics to be of fundamental importance for future advances in this field.

15. SUBJECT TERMS
EOARD, Quantum Entanglement, Quantum Information Processing

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 12	19a. NAME OF RESPONSIBLE PERSON SCOTT DUDLEY, Lt Col, USAF
a. REPORT UNCLAS	b. ABSTRACT UNCLAS	c. THIS PAGE UNCLAS			19b. TELEPHONE NUMBER (Include area code) +44 (0)1895 616162

Multiparticle Entanglement and Spatial Addressability of Ultracold Atoms in Optical Lattices



*Prof. Dr. Immanuel Bloch
Dr. Stefan Kuhr
Johannes Gutenberg-University, Mainz, Germany*

Award-No. FA8655-07-1-3090
Report – End of Phase 1 - 25 January 2009

Recent Results and Current Status:

Our research work focusses on two projects with ultracold atoms in optical lattices. One is carried out on an existing experiment and the other one is carried out on a completely new experimental apparatus.

Project part I:

Multiparticle Entanglement of Ultracold Atoms in Optical Lattices

The first part of our research project is on the generation of robust multiparticle entanglement in optical lattices with low decoherence rates. These entangled states can be used e.g. as a resource for quantum information processing and improved atom interferometers. Important results such as the detection of high order tunnelling processes and superexchange interactions have been realized.

The setup uses a superlattice system consisting of two different laser wavelengths. Technical problems with the superlattice laser system have delayed work on this project, as we had to wait for a repair from the manufacturer (NP Photonics, Tucson, USA). The repaired system is currently fully operational again in the laboratory and we expect to resume work on the project during the next weeks. While waiting for the laser repair, we explored a novel technique to use ultracold atoms in a Mott insulating state as a medium for quantum storage of light. The goal is to transfer quantum states from light field to atomic spin waves in the lattice and back onto light fields.

During the first year the following steps have been achieved (see detailed description of the first points in the interim report):

- **Setup of a superlattice system and Loading of atoms in the superlattice potential**

This setup uses two lasers at 765 nm and 1530 nm. Superimposing two standing waves with these wavelengths creates an array of double well potentials. Shifting the relative phase of the two laser beams forming the double well potential, can dynamically change the double well potential. In this way, pattern loading of the atoms can be achieved, such as e.g. the deterministic loading of two atoms in each left potential of the double well.

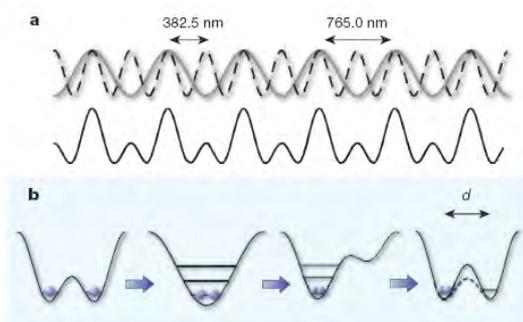


Fig. 1: Schematics of double-well generation, loading and detection sequences. a) Superimposing two optical lattice potentials differing in period by a factor of two creates an array of double-well potentials. b) Preparation sequence. An initially large well is split into a biased double well potential such that each left well is populated. The bias is then removed and the central barrier lowered to initiate the tunnelling dynamics.

- **Spin changing collisions in optical superlattices and preparation of antiferromagnetic ordering**

Using spin changing collisions we could prepare spin triplet pairs of the form $|+1;-1\rangle+|-1;+1\rangle/\sqrt{2}$, where the two magnetic sublevels $|m_F = \pm 1\rangle$ correspond to the two spin states $|\uparrow\rangle$ and $|\downarrow\rangle$. Using a magnetic field gradient and a controlled ramping of the double well lattice, we could prepare an antiferromagnetic order with a very high fidelity of 99% along the axis of the superlattice. The mean population- and spin imbalance of the ensemble of double wells was detected by applying a mapping technique combined with a Stern-Gerlach filter.

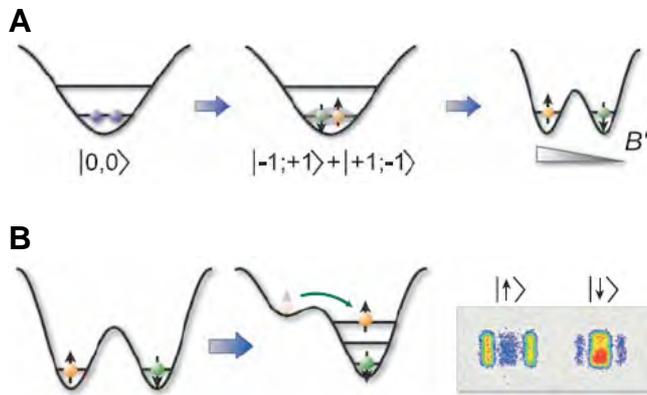


Fig. 2. Preparation of an antiferromagnetically ordered state: A) Spin triplet pairs are created on doubly occupied lattice sites and subsequently split under the influence of a magnetic field gradient B' to obtain antiferromagnetic Néel order. B) Detection of the population and spin imbalance. The population of the left well is transferred to a higher vibrational level of the underlying long-lattice well. Subsequent band mapping and a Stern-Gerlach filter allows to determine the population- and spin imbalance of the two potential wells.

- **Detection of high order tunnelling processes**

In the regime of strong repulsive interactions, two atoms located on one side of the barrier tunnel together as a pair in a second-order co-tunnelling process. Second-order tunnelling events are the dominating dynamical effects in the strongly interacting regime have not been previously observed with ultracold atoms. By recording the atom position and phase coherence over time, we fully characterized the tunnelling process for a single atom as well as the correlated dynamics of a pair of atoms for weak and strong interactions.

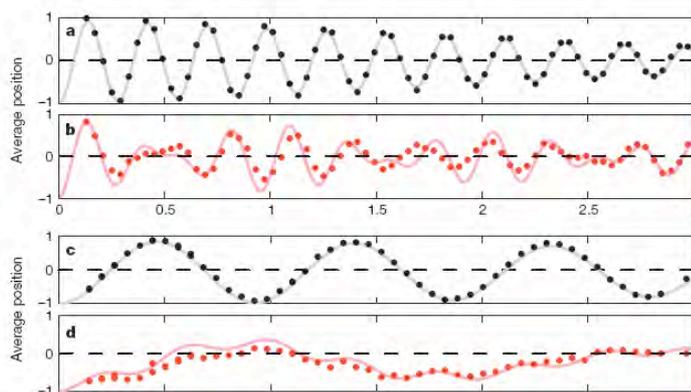


Fig. 3: Tunnelling dynamics. Full dynamical tunnelling evolution for single atoms and atom pairs in the weakly (a, b) and strongly (c, d) interacting regime after initially preparing all particles localized on the left side of the double well. The black dots denote the single-atom position signal. The red dots show the atom-pair signal. d) For strong interactions, first-order tunnelling is suppressed. The main dynamical

cal process is pair tunnelling.

- **Detection of superexchange interactions**

We also measured coherent superexchange-mediated spin dynamics after preparing the atoms in an antiferromagnetically ordered state (see above), By dynamically modifying the potential bias between neighboring lattice sites, the magnitude and sign of the superexchange interaction could be controlled. These quantum mechanical superexchange interactions are of great importance in other systems since they form the basis of quantum magnetism in strongly correlated electronic media.

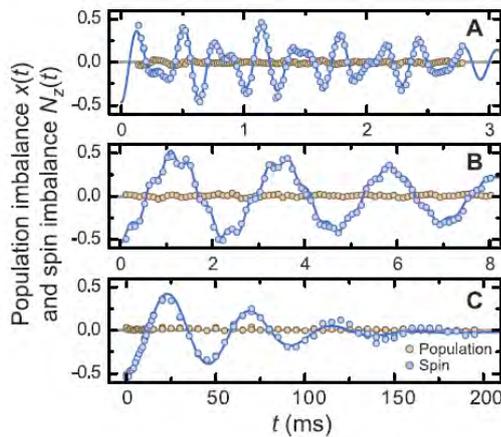


Fig. 4: Spin and population dynamics in symmetric double wells. The time evolution of the mean spin (blue circles) and population imbalance (brown circles) are shown for three barrier depths within the double-well potential: for different values of lattice depth and tunnel coupling strength. The measured traces for the spin imbalance are fitted with the sum of two damped sine waves (blue lines). The population imbalance stays flat for all traces.

- **Electromagnetically induced transparency and light storage in a Mott insulator**

Electromagnetically induced transparency is a quantum effect that allows an incoming light pulse to be converted into a stationary superposition of internal states and back into a light pulse. In the past, this effect has successfully been used to map quantum states of light onto cold atomic ensembles. However in atomic ensembles, the light storage times usually do not exceed a few milliseconds. Atoms in a Mott insulator (MI) state in a deep 3d optical lattice with unity filling experience no diffusion and no collisional interaction.

We could experimentally demonstrate electromagnetically induced transparency and light storage with ultracold rubidium atoms in a Mott insulating state. We have observed light storage times of more than 200 ms, to our knowledge the longest ever achieved in ultracold atomic samples.

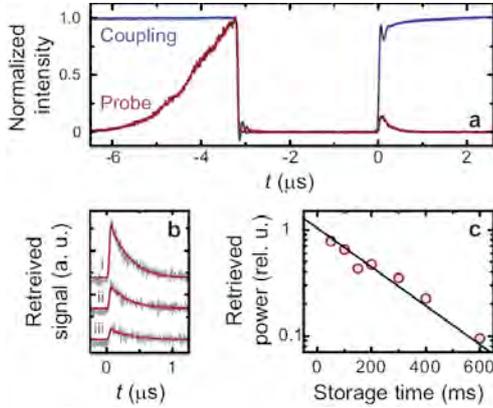


Fig. 5: Light storage. (a) Intensity of coupling (probe) beams, recorded on a photodiode before (after) the atomic sample during a light storage experiment with 3 μs storage time in a thermal cloud. (b) Retrieved pulses for storage times of $t = 1$ ms, 200 ms, 400 ms (from top to bottom) in a Mott insulator. (c) Retrieved pulse energy as a function of t . The line is an exponential fit with decay time $\tau = 238(20)$ ms.

- **Controlled manipulation of atomic spin states**

The small dephasing observed in a Mott insulating state makes the system suitable for the controlled manipulation of the atomic spin states and thereby processing of the stored light pulse. In this context we demonstrated that light pulses could first be stored in the Mott insulator, the atomic spin excitation then manipulated and subsequently mapped back efficiently into a directional emitted pulse of light. As an example of such a spin-wave manipulation, we imprint a “phase gradient” across the atomic sample using a spatially varying differential light shift of the two ground state levels. This spatial phase gradient results in a controlled change of direction of the restored pulse.

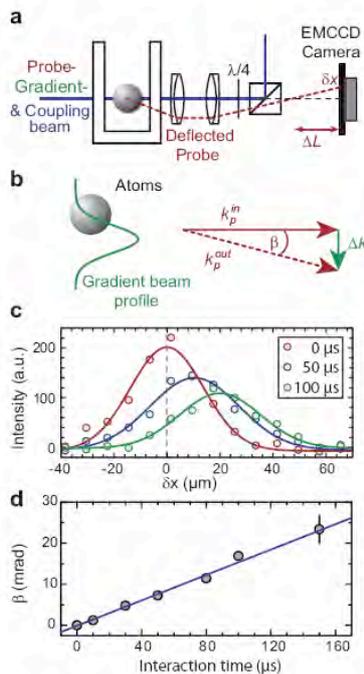


Fig. 6: Angular deflection of a stored light pulse. (a) The deflected light pulse is detected with an EMCCD camera. (b) A detuned laser beam with a spatially varying intensity profile across the atoms creates a spatial phase gradient via the differential light shift. (c) Row sums of the CCD images from the detected light pulse for different interaction times. Each curve is averaged over 5 runs and the background due to the coupling beam is subtracted. (d) Deflection angle as a function of the interaction time with the gradient beam. The blue line is a linear fit.

The next immediate steps will consist in:

- Creation and validation of singlet Bell pairs for massive creation of entangled states
- Preparation of entangled states in 1D coupled ladder systems
- Continue research on the light storage and EIT. Use of the retrieved light pulses to probe dephasing and spin structure in the lattice.

Publications:

1. S. Fölling, S. Trotzky, P. Cheinet, M. Feld, R. Saers, A. Widera, T. Müller, I. Bloch, *Direct Observation of Second Order Atom Tunnelling*, Nature **448**, 1029 (2007).
2. S. Trotzky, P. Cheinet, S. Fölling, M. Feld, U. Schnorrberger, A. M. Rey, A. Polkovnikov, E. A. Demler, M. D. Lukin, I. Bloch, *Time-resolved Observation and Control of Superexchange Interactions with Ultracold Atoms in Optical Lattices*, Science **319**, 295 (2008).
3. I. Bloch, *Quantum coherence and entanglement with ultracold atoms in optical lattices*, Nature **453**, 1016 (2008).
4. U. Schnorrberger, J. D. Thompson, S. Trotzky, R. Pugatch, N. Davidson, S. Kuhr, and I. Bloch, *Electromagnetically induced transparency and light storage in a Mott insulator*, submitted to Phys. Rev. Lett.

Project part II:

Spatial Addressability of Ultracold Atoms in Optical Lattices

This part of the proposal deals with the individual detection and addressing of single sites in an optical lattice. Single site resolution will be obtained with a specially designed high resolution optical imaging system. This project is new and required the construction of a new experimental apparatus. The first year of the funding period was devoted to construction of the apparatus and the laser system. We carried out preliminary experiments on laser cooling the atoms in a preliminary vacuum chamber.

- **Construction and setup of a new vacuum chamber**

We have found that the existing vacuum chamber was not really adapted to the requirements of the experiment. First, we could not reach the required low vacuum pressure which lead to a significant reduction of the lifetimes of the atoms in the magneto-optical and magnetic traps. For this reason, it was impossible up to now to cool the atoms to very low temperatures to reach the Bose-Einstein condensation. A second problem of the old setup was that the glass windows were too much deformed which would make it impossible to detect the atoms with the ultrahigh resolution imaging system.

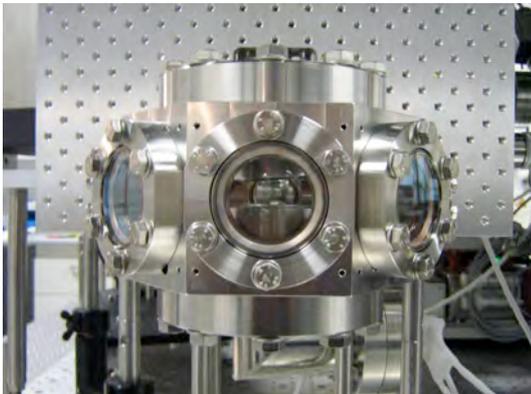


Fig. 7: Photograph of the new vacuum chamber. The chamber is made of special non-magnetic stainless steel and contains a deformation-free window through which the high resolution imaging of the atoms will be performed.

The new chamber was built in the second half of the year 2008. Similar to the old chamber, the new vacuum chamber consists of two separate chambers. One part is used to create a two-dimensional magneto-optical trap as a source of cold rubidium atoms. This part has a high rubidium background pressure to maximise the atomic flux. The second part is the main chamber, in which the real experiment takes place. The two parts are interconnected with a small tube to maintain a pressure difference. Using a combination of different pumping techniques (ion pumps, titanium sublimator, non-evaporable getters) we could reach a pressure of approx. 2×10^{-11} mbar in the main chamber, which is one order of magnitude better than in the old chamber.

When assembling the chamber, we also managed to mound the critical glass window with only deformations that are small enough to guarantee a good image quality. The deformations were measured during the assembly and after bakeout of the chamber with a small mobile Fizeau interferometer.

- **Reconstruction and improvement of the double MOT system**

In our apparatus, we use a system consisting of two magneto optical traps (MOTs). A 2D-MOT serves as a beam source for cold rubidium atoms, which are captured and cooled further in a 3D-MOT. The laser system used for this purpose consists of diode lasers and tapered amplifiers with computer controlled frequency and amplitudes over wide tuning ranges. We improved the beam source of preliminary setup by adding two cooling beams along the axis of the 2D-MOT. This improved the efficiency of the 2D-MOT by more than a factor to about 2×10^9 atoms/sec captured in the 3D-MOT.

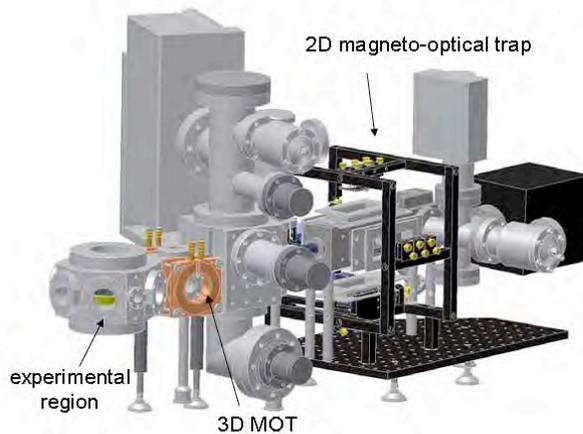


Fig. 7. Schematic of the new vacuum chamber. A 2D magneto-optical trap (MOT) acts as a source of cold atom, which are recaptured in the 3D MOT. Using an optical dipole trap these atoms shall be transported to the experimental region, where the optical lattices and the high resolution imaging system will be located.

- **Magnetic trapping and evaporation**

We initially planned to realize a Bose-Einstein condensate in an all-optical trap consisting of a compressible crossed optical dipole trap (see interim report). Although we successfully trapped and cooled atoms in that device, we found that the dipole trap setup was not reliable enough and that we could not efficiently cool enough atoms to quantum degeneracy. We therefore decided to use a magnetic trap instead. For this purpose we developed and designed new water cooled magnetic coils which can sustain high continuous currents of up to 50A. With these coils we could build magnetic traps with field gradients of more than 100 G/cm. We could transfer more than 3×10^9 atoms into the magnetic trap and cool them using evaporation via microwave fields.

- **Setup of the optical lattice system**

In parallel to the ongoing work on the experiment, we are setting up the laser system, optics and optomechanics for the optical lattices in a neighbouring lab. As a laser we use a Yb fiber laser at 1064 nm. The design of the mechanical parts (breadboards etc) was especially optimized to minimize vibrations. All of the axes of the three dimen-

sional optical lattice can be superimposed by an imaging beam and beams for the optical molasses at wavelengths of 780 nm and 420 nm.

The next immediate steps will consist in:

- Integration of an optical dipole trap. We will try to reach a Bose Einstein Condensate in a hybrid trap consisting of the magnetic trap and a dipole trap.
- Integration of the prepared optical lattice setup into the experiment. Transport of the atoms with the dipole trap to region where the optical lattice and the actual experiment is located.
- Test and assembly of the high resolution imaging optics. The high resolution imaging optics has to be accurately positioned with respect to the vacuum window. For this purpose a special micropositioning system has to be developed. The imaging system has to be assembled and characterized using test targets.

Delarations, Disclaimers and Acknowledgments

Acknowledgement of Support: This material is based upon work supported by the European Office of Aerospace Research and Development, Air Force Office of Scientific Research, Air Force Laboratory, under contract FA8655-07-1-3090.

Disclaimer: Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the European Office of Aerospace Research and Development, Air Force Office of Scientific Research, Air Force Laboratory.

The Contractor, Professor Immanuel Bloch, hereby declares that, to the best of his knowledge and belief, the technical data delivered herewith under Contract No. FA8655-07-1-3090 is complete, accurate, and complies with all requirements of the contract.

DATE: _02/02/2009_____

Name and Title of Authorized Official:



Prof. Dr. Immanuel Bloch _____

I certify that there were no subject inventions to declare as defined in FAR 52.227-13, during the performance of this contract.

DATE: _____

Name and Title of Authorized Official:
