Fermionic atoms in an optical lattice: a new synthetic material

Michael Köhl and Tilman Esslinger,
Quantum Optics, ETH Zürich • 8093 Zürich • Switzerland

The demonstration of Bose-Einstein condensation, ten years ago, has initiated a wave of research on quantum degenerate gases [1,2]. Close to absolute zero temperature the atoms almost come to a standstill and a window on the quantum nature of many-particle systems opens up. It has now become possible to establish a link between quantum gases and the physics of electrons in a solid. Ultracold fermionic atoms have been trapped in a crystal structure formed by interfering laser beams [3,4]. The properties of this synthetic material can be changed at will. Switching between conducting and insulating states has been demonstrated, and by tuning the interactions between the atoms, an intriguing regime beyond basic solid state models has become accessible. Even the dimensionality of the system is controlled. One-dimensional Fermi gases have been created and weakly bound molecules, existing only in one dimension, have been observed [5]. The unique versatility of atoms in these optical lattices makes researchers optimistic to study a whole range of phenomena linked to solid-state physics. Text-book style experiments, answers to open questions and new effects will probably be seen. For example, it has been proposed that the physics underlying high-temperature superconductivity may be mimicked in these systems [6,7]. In the following we give a general introduction to this novel research field, describe first experimental results on fermions in optical lattices and provide an outlook to this vibrant field.

Creating ultracold gases

The route towards zero temperature in a gas of atoms is a narrow path which circumvents solidification by keeping the atomic cloud at very low densities. To go along this track the experiments exploit the mechanical effect of laser light to slow down atoms, followed by evaporative cooling of the atoms in a magnetic trap. Upon reaching temperatures of 100 Nanokelvin and below, the experimental efforts are rewarded with a quantum many-body system of ultimate controllability and access to microscopic understanding. The achievement of Bose-Einstein condensation in a weakly interacting gas of atoms has given a first taste of the new possibilities [1,2]. It could be witnessed how the gas condensed into a single quantum state displaying the behaviour of one quantum mechanical wave function. The investigation of weakly interacting Bose-Einstein condensates were soon accompanied by successful efforts to create quantum degenerate Fermi gases [8], which exhibit a fundamentally different behaviour due to Pauli's exclusion principle.

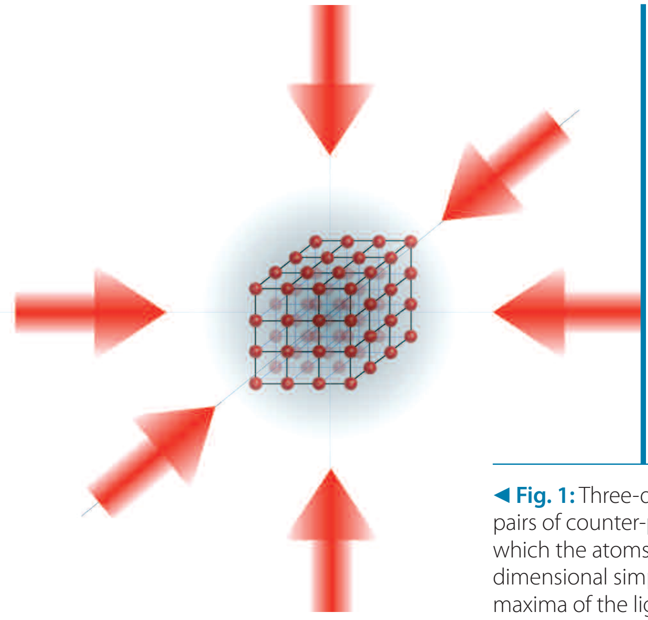
Optical Lattices

An intriguing tool to manipulate ultracold quantum gases is the optical lattice. It is created by up to three mutually perpendicular standing laser waves. Therein the atoms experience a periodic potential due to the interaction of the induced electric dipole moment of the atoms with the laser light [9]. For frequencies of the lattice laser which are below the atomic resonance frequency the atoms are attracted towards regions of high laser intensity. Therefore an anti-node of the standing wave acts as a lattice site. Three standing waves produce a cubic lattice structure with a separation of typically 400-500 nm between adjacent lattice sites, see figure 1. In addition, the Gaussian beam profile gives rise to a force pointing towards the beam centre, where the atoms are harmonically confined. The periodicity of the optical lattice results in a band structure for the trapped atoms, which is a particularly suitable picture if atom-atom collisions can be neglected. As we will see below, the physics of an interacting quantum gas in the optical lattice can often be described by the Hubbard model, which plays a key role in the description of many intriguing phenomena in modern condensed matter physics.

Imaging Fermi-surfaces

In the experiment [4] we sympathetically cool a gas of fermionic ^{40}K atoms with bosonic ^{87}Rb atoms, the latter being subjected to forced evaporation. After reaching quantum degeneracy for both species we remove all rubidium atoms from the trap. For the potassium atoms we reach a final temperature of $T/T_F = 0.25$ (T_F: Fermi temperature) with up to $2{\cdot}10^5$ particles before loading them into a three-dimensional optical lattice.

Assuming zero temperature, we expect that all states up to the Fermi energy E_F are occupied in the optical lattice. For a homogeneous periodic potential the lowest band would be only partially filled if the Fermi energy is lower than the width of this band. The underlying harmonic trapping potential, present in the experiment, leads to a quadratic increase of the potential energy with the distance from the trap centre. Hence, for a given Fermi energy the filling of the lattice is maximal in the centre of the trap and decreases



◀ **Fig. 1:** Three-dimensional optical lattice. An ultracold gas of atoms is trapped by three pairs of counter-propagating laser beams. Each pair produces a standing laser wave in which the atoms experience a periodic potential. All three pairs generate a three-dimensional simple cubic lattice structure, where the atoms are trapped in the intensity maxima of the light.

Article available at http://www.europhysicsnews.org or http://dx.doi.org/10.1051/epn:2006201

towards the edges of the trap [10]. A band insulator starts to form in the centre of the trap when the Fermi energy reaches the width of the lowest band. A further increase of the Fermi energy, which corresponds to a larger number of atoms in the trap, enlarges the size of the insulating region until the Fermi energy matches the energy of the second band which is then filled similarly.

In order to gain experimental insight into the filling of the optical lattice we apply a method which allows us to directly observe the Fermi surfaces. The intensity of the optical lattice is slowly ramped down as to avoid non-adiabatic transitions of the atoms from one band to another band. As illustrated in Fig. 2 this maps the quasi-momentum distribution of the atoms inside the lattice onto the real momentum distribution of the expanding cloud [11]. This distribution is then measured by absorption imaging of the cloud after ballistic expansion. The shape of the distribution corresponds to the projection of the Fermi surface for different fillings, as shown in Fig. 3.

By changing the intensity of the optical lattice beams we could reversibly vary between a conducting state and a band insulating state. Initially a conducting state is prepared by loading the atoms into an optical lattice with comparatively low beam intensities, so that the overall harmonic confinement is comparatively weak and the bandwidth larger than the Fermi energy. By increasing the laser power the atoms are pushed towards the trap centre where a band insulator starts to form. Our studies show that this process is reversible if carried out slow enough to allow the atoms sufficient time to tunnel to neighbouring sites [4].

Fermionic atoms interacting in an optical lattice: The Hubbard model and beyond

Due to the low temperatures in the experiment the energy between colliding atoms is so low that collisions are dominated by partial waves with zero angular momentum, i.e. s-waves. Consequently, a spin-polarized Fermi gas is effectively non-interacting, since Pauli's principle does not allow s-wave collisions, which are of even parity. However, the situation is different if the Fermi gas is prepared in an equal mixture of two different spin states, between which s-wave collisions are permitted. The s-wave collisions are characterised by a scattering length *a*, which is positive for repulsive and negative for attractive interactions. In the experiment the potassium gas is prepared in two different magnetic sublevels of the hyperfine ground state, which represent the two spin states.

The physics of interacting atoms in the optical lattice can be accessed by an important simplification. It is possible to prepare all atoms in the lowest band and regard the atoms as hopping from one lattice site to the next, as illustrated in Fig. 4. This motion is characterized by the tunnelling matrix element *J* between adjacent sites. If two atoms happen to be on the same site the atom-atom collisions give rise to a short range interaction *U*, which is proportional to the scattering length *a*. This was pointed out by D. Jaksch and coworkers who suggested that neutral atoms in an optical lattice are well described by a Hubbard Hamiltonian [12]. The proposed ideas led to the experimental observation of a transitions from a superfluid to a Mott-insulating phase for bosons, using a Bose-Einstein condensate loaded into a three dimensional optical lattice [13,14].

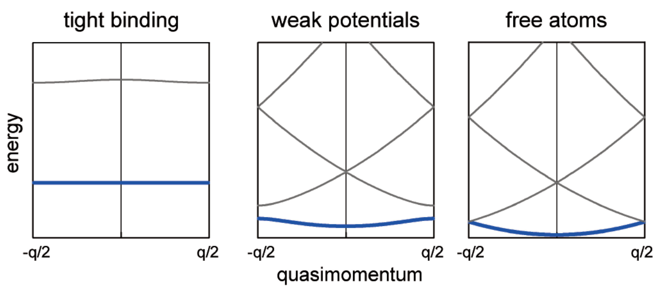
For fermionic atoms the Hubbard Hamiltonian in an optical lattice reads:

$$H = -J \sum_{\{i,j\},\sigma} \hat{c}^{\dagger}_{i,\sigma}\hat{c}_{j,\sigma} + \sum_{i} \varepsilon_i \hat{n}_i + U \sum_{i} \hat{n}_{i,\uparrow}\hat{n}_{i,\downarrow}$$

The first term contains the kinetic energy and is proportional to the tunnelling matrix element *J*. The operators $\hat{c}^{\dagger}_{i,\sigma}$ and $\hat{c}_{j,\sigma}$ are the fermionic creation and annihilation operators for a particle in the spin state σ (up or down) at lattice sites *i* and *j*. The occupation number of the site *i* is given by $\hat{n}_{i,\sigma}$. The second term takes account of the additional harmonic confinement of the optical lattice. The last term describes the interaction energy in the system and is determined by the on-site interaction *U*.

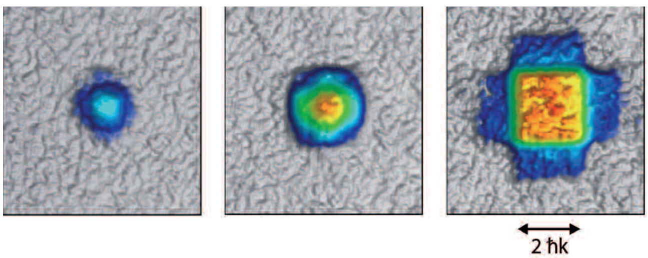
It is the control of parameters which makes the atomic realisation of Hubbard models unique. The intensity of the laser standing waves controls the barrier between the lattice sites, i.e. the tunnel coupling *J*. This allows tuning of the kinetic energy and of the time scale for transport. It also gives direct access to the dimensionality of the system. For example, a one-dimensional situation is created by suppressing tunnelling in two directions, using two standing waves with very high intensities. Further, the on-site interaction *U* can be tuned to negative or positive values. Even the statistics of the particles on the lattice can be changed by forming bosonic diatomic molecules from two fermionic atoms of different spin.

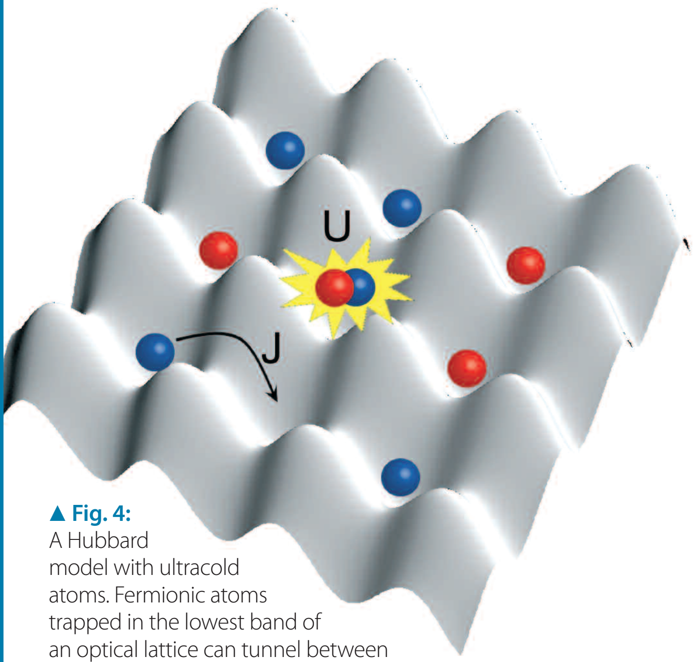
In the experiment we make use of a Feshbach resonance to tune the collisional interaction between two atoms, i.e. the *U* in



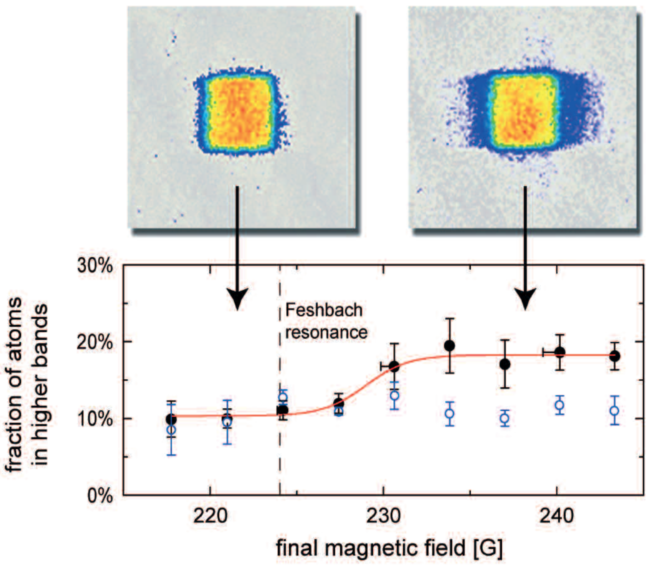
▲ **Fig.2:** Measuring the quasimomentum distribution. If the lattice potential is adiabatically lowered the quasimomentum distribution is mapped onto real momentum, since quasi-momentum is conserved. As the laser intensity is reduced, the lowest energy band transforms from being practically flat, in the tight binding limit, to a parabolic dispersion relation of free particles. Adiabaticity requires the process being slow enough as to avoid transitions between different bands. For example, the quasimomentum distribution of a completely filled lowest band is mapped onto a momentum distribution with momenta between $-\hbar q/2$ and $+\hbar q/2$, where *q* is the spatial frequency of the lattice potential.

▼ **Fig. 3:** Observing the Fermi surface. The absorption images are taken after adiabatically lowering the lattice potential followed by 9 ms of ballistic expansion. The false colour distributions are projections on the imaging plane and represent the quasimomentum of the atoms in the optical lattice. The boundary of the distribution reveals the Fermi surface. The atomic density increases from left to right. At low densities the Fermi surface is of spherical shape and the corresponding projection is seen. With increasing atomic density and atom number in the trap the Fermi surface develops a more complex structure showing extensions towards the boundary of the first Brillouin zone, as seen in the middle. In the frame on the right hand side the filling of the lattice in the trap centre exceeds unity such that higher bands are populated which show up beyond the square shape of the first Brillouin zone.





▲ **Fig. 4:** A Hubbard model with ultracold atoms. Fermionic atoms trapped in the lowest band of an optical lattice can tunnel between lattice sites with a tunnelling rate *J*. Due to Pauli's principle, tunnelling is only possible if the final lattice site is empty or occupied with an atom with a different spin. Two atoms with opposite spin localized at the same lattice site have an interaction energy *U*, which can be likewise positive (repulsive interaction) or negative (attractive interaction). The interplay between *J* and *U* and the filling determines the physics of the system.



▲ **Fig. 5:** Interaction induced coupling between Bloch bands. If the interaction energy U between particles on the same lattice site becomes comparable to the band gap, the single band Hubbard model breaks down. The strong interaction leads to a coupling between different bands. The two false color images show the measured quasimomentum distribution before (left) and after (right) strong interaction between the atoms. The interaction has been induced by sweeping the magnetic field across a Feshbach resonance. Quasimomentum states outside the first Brillouin zone become occupied which demonstrates the interaction induced coupling between the bands. The transfer of population occurs in one direction only, since a lower value for the intensity of the lattice beam has been chosen for this direction. (The figure is reprinted with permission from M. Köhl, H. Moritz, T. Stöferle, K. Günter, T. Esslinger, Phys. Rev. Lett. 94, 080403 (2005). Copyright 2005 by the American Physical Society.)

the Hubbard model. In a Feshbach resonance an applied magnetic field induces a coupling between different collisional channels which leads to a resonant behaviour of the scattering length a as a function of the magnetic field. Starting from a background value a_{bg} the scattering length increases with increasing magnetic field and diverges to plus infinity at the resonance position, then it switches to minus infinity before smoothly approaching the background value again. The typical width of such a resonance is a few Gauss.

To investigate the atom-atom interactions in the optical lattice we prepare the Fermi gas in two different spin components and produce a band insulator in the lowest band for each component, i.e. per lattice site there is one particle in each spin state. Starting from a weakly interacting situation we ramp the magnetic field over the resonance of the scattering length. After crossing the resonance we measured the population in each band and observed an increased population in the higher bands, see Fig. 5. Due to the large increase of the interaction we actually entered a regime beyond the standard Hubbard model. For a full description of the experiment higher bands would have to be taken into account since the on-site interaction exceeds the band gap. These models are notoriously difficult and a simpler approach to get a rough understanding of the experimental observations is to consider the low-tunneling limit, where we can describe each lattice site as a harmonic oscillator with two interacting particles. This model can be solved analytically [15] and shows that crossing the Feshbach resonance for the scattering length transfers part of the population to higher harmonic oscillator states, which corresponds to the observed population of higher bands. Although this approach does not give satisfying quantitative agreement with our observations, it gives qualitative insight.

Fermi gases in one spatial dimension: Confinement induced molecules

Quantum gases in one spatial dimension are a unique quantum model system due to the dominant role of quantum fluctuations. Many characteristics are not encountered in two or three dimensions, and, one-dimensional systems provide an ideal testing ground for quantum many-body physics due to the existence of exactly solvable models. The experimental research on one-dimensional atomic Fermi gases is only just beginning and we want to briefly discuss the first results.

An optical lattice produced from two standing laser waves generates a potential resembling an array of tubes, as shown in the upper part of Fig. 6. In each tube the particles can move only along the tube axis whilst the motion in the radial direction is frozen out. We used this lattice configuration to realize a quantum degenerate one-dimensional atomic Fermi gas. With the fermionic potassium atoms in two different spin states this can be considered to be a Luttinger liquid with tunable interactions. In a first experiment we studied the atom-atom interactions in the presence of a Feshbach resonance and were able to observe a new form of weakly bound molecules which exist only when the motion of the particles is restricted to one spatial dimension. Our experimental findings confirm the theoretical prediction for a one-dimensional atom gas that there always exists a bound state, irrespective of the sign of the scattering lengths. This contrasts with the usual three-dimensional situation, in which a stable molecular bound state is found only for positive values of the scattering length. In the one-dimensional case, the zero-point energy, due to the confinement in the radial direction, turns out to be enough to stabilize a bound molecular state. In the experiment we used radio-frequency spectroscopy to measure the dissociation energy of the molecular states and were thereby able to quantitatively verify the theoretical prediction, see Fig. 6.

Outlook

The physics of fermionic atoms in optical lattices covers a wide range of concepts in modern condensed matter physics and beyond. Experiments which now appear to be within reach are the creation of a Mott-insulating or an anti-ferromagnetic phase, where the repulsive interaction between atoms in different spins should cause a pattern with alternating spin up and spin down. For attractive interactions, it should be possible to study the superfluid properties in the BEC-BCS crossover regime inside an optical lattice. In general, fermionic atoms in optical lattices are much closer to real materials and provide a richer physics than their bosonic counterparts, but they are also more difficult to understand. A particular tantalizing prospect is, that fermionic atoms in optical lattices may provide solutions to unanswered question in condensed matter physics, such as high-temperature superconductivity. The challenge here is twofold. One central requirement is to reach extremely low temperatures inside the optical lattice. The second challenge is how to extract the information on the quantum many-body state from the experiment. To test new approaches and techniques with optical lattices one-dimensional systems will play a crucial role since they allow a comparison between exactly solvable models and the experimental findings. The experiments can then easily be extended to two or three dimensions. In the future, optical lattices of different geometric structure, superlattices or lattices with disorder, will most likely be implemented in experiments. New directions include very strong interactions, mixtures of bosons and fermions and polar molecules. Besides simulating quantum systems, optical lattices are a promising system for the development of a quantum computer. The optical lattice can be regarded as a quantum register with each atom on a lattice site acting as a quantum bit. Whilst the initial preparation of such a quantum register with thousands of qubit seems manageable, it is the controlled interaction between different atoms and the readout of single bits which represents the challenge. ■

Acknowledgements:

The authors would like to thank the team members Kenneth Günter, Henning Moritz and Thilo Stöferle. We acknowledge funding by the SNF (Swiss Science Foundation), OLAQUI (EU FP6-511057), Qudedis (ESF), and QSIT.

About the authors:

Michael Köhl studied physics in Heidelberg and Frankfurt and carried out his Diploma thesis at the Massachusetts Institute of Technology. He received his PhD from the University of Munich in 2001. Since then he is a research assistant at ETH Zürich.

Tilman Esslinger studied Physics in Munich and Edinburgh. For his PhD he joined the Max-Planck-Institute for Quantum Optics in Garching. Between 1995 and 2001 he was a researcher at the University of Munich. Since 2001 he is a full professor at ETH Zürich.

More information about the research group can be found at www.quantumoptics.ethz.ch

References

[1] M. H. Anderson, J.R. Ensher, M.R. Matthews, C.E. Wieman, E. A. Cornell, *Science* **269**, 198 (1995).

[2] K. B. Davis, M. -O. Mewes, M. R. Andrews, N. J. van Druten, D. S. Durfee, D. M. Kurn, and W. Ketterle, *Phys. Rev. Lett.* **75**, 3969 (1995).

[3] G. Modugno, F. Ferlaino, R. Heidemann, G. Roati, and M. Inguscio, *Phys. Rev. A* **68**, 011601(R) (2003).

[4] M. Köhl, H. Moritz, T. Stöferle, K. Günter, and T. Esslinger, *Phys. Rev. Lett.* **94**, 080403 (2005).

[5] H. Moritz, T. Stöferle, K. Günter, M. Köhl, and T. Esslinger, *Phys. Rev. Lett.* **94**, 210401 (2005).

[6] W. Hofstetter, J. I. Cirac, P. Zoller, E. Demler, and M. D. Lukin, *Phys. Rev. Lett.* **89**, 220407 (2002).

[7] S. Trebst, U. Schollwoeck, M. Troyer, and P. Zoller, cond-mat/0506809.

[8] B. DeMarco and D. S. Jin, *Science* **285**, 1703 (1999).

[9] V. L. Letokhov, *JETP Lett.* **7**, 272 (1968).

[10] M. Rigol, A. Muramatsu, G. G. Batrouni, and R. T. Scalettar, *Phys. Rev. Lett.* **91**, 130403 (2003).

[11] A. Kastberg, W. D. Phillips, S. L. Rolston, R. J. C. Spreeuw, and P. S. Jessen, *Phys. Rev. Lett.* **74**, 1542 (1995).

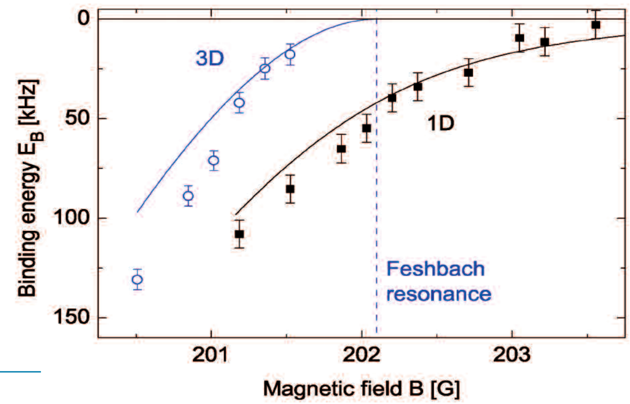
[12] D. Jaksch, C. Bruder, J. I. Cirac, C. W. Gardiner, and P. Zoller, *Phys. Rev. Lett.* **81**, 3108 (1998).

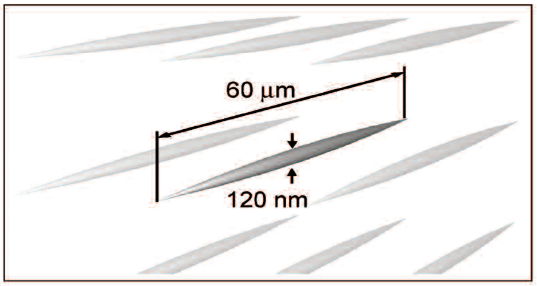
[13] M. Greiner, O. Mandel, T. Esslinger, T. W. Hänsch, and I. Bloch, *Nature* (London) **415**, 39 (2002).

[14] T. Stöferle, H. Moritz, C. Schori, M. Köhl, and T. Esslinger, *Phys. Rev. Lett.* **92**, 130403 (2004).

[15] T. Busch, B.G. Englert, K. Rzazewski, and M. Wilkens, *Found. Phys.* **28**, 549 (1998).

[16] M. Olshanii, *Phys. Rev. Lett.* **81**, 938 (1998).





► **Fig. 6:** A one-dimensional atomic Fermi gas.
Top: Measured binding energy of a pair of atoms. In a three-dimensional gas, bound states exist only on the left side of the Feshbach resonance, where the scattering length is positive. In contrast, in one dimension confinement-induced molecules exist for any value of the scattering length. (The figure is reprinted with permission from H. Moritz, T. Stöferle, K. Günter, M. Köhl, T. Esslinger, Phys. Rev. Lett. 94, 210401 (2005). Copyright 2005 by the American Physical Society.)
Bottom: An optical lattice made from two standing laser waves is used to create an array of one-dimensional quantum gases. Radially the gas occupies only the vibrational ground state of the potential and the motion is restricted to zero-point oscillations. In the axial direction the gas is weakly confined and the physics in this dimension is studied.