Confinement Induced Molecules in a 1D Fermi Gas

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We have observed two-particle bound states of atoms confined in a one-dimensional matter waveguide. These bound states exist irrespective of the sign of the scattering length, contrary to the situation in free space. Using radio-frequency spectroscopy we have measured the binding energy of these dimers as a function of the scattering length and confinement and find good agreement with theory. The strongly interacting one-dimensional Fermi gas which we create in an optical lattice represents a realization of a tunable Luttinger liquid.

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The study of two particles forming a bound state has a long history both in physics and chemistry because it constitutes the most elementary chemical reaction. In most situations, such as atoms in the gas phase or in a liquid, the two particles can be considered as being in free space and their collisions can be described by standard quantum mechanical scattering theory. For ultracold atoms undergoing s-wave interaction, a bound molecular state is only supported when the scattering length between the atoms is positive whereas for negative scattering length the bound state is absent [1].

Weakly bound diatomic molecules in ultracold atomic gases can be produced using magnetic field induced Feshbach resonances [2–10]. The scattering length between the atoms and thus the binding energy of the molecules can be tuned by an external magnetic field. The fundamental property that a bound state exists only for positive scattering length was clearly revealed experimentally [3]. For negative scattering length pairing due to many-body effects has been observed in fermionic atoms [11,12]. In this work we report on the observation of bound states of atoms with negative scattering length where the particles are subject to one-dimensional confinement. The reduced dimensionality strongly affects the two-particle physics provided that the scattering length and the size of the transverse ground state are similar [13–16]. This contrasts with previous studies of interaction-induced phenomena in one-dimensional quantum systems where the reduced dimensionality affects only the many-body properties, such as spin-charge separation in cuprates [17], the Mott insulator transition for bosonic atoms in an optical lattice [18], and the fermionization of a Bose gas [19–21].

Tight transverse confinement alters the scattering properties of two colliding atoms fundamentally and a bound state exists irrespective of the sign of the scattering length. This peculiar behavior in a one-dimensional system arises from the additional radial confinement which raises the continuum energy to the zero point energy of the confining potential, e.g., the two-dimensional harmonic oscillator ground state energy $\hbar\omega_r$. The energy of a bound or quasibound state remains nearly unaffected by the external confinement as long as the effective range of the interaction is small compared to the extension of the confined ground state. Therefore, a quasibound state, which for negative scattering length a lies above the continuum in free space, is below the new continuum in the confined system.

The binding energy E_B of dimers in a one-dimensional gas is given by [15]

$$\frac{a}{a_r} = -\frac{\sqrt{2}}{\zeta(1/2, -E_B/2\hbar\omega_r)}, \tag{1}$$

where $a_r = \sqrt{\hbar/m\omega_r}$ is the extension of the transverse ground state (with m being the atomic mass) and ζ denotes the Hurwitz zeta function. For negative a and $|a| \ll a_r$, a weakly bound state with $E_B \approx m\omega_r^2 a^2$ exists which has a very anisotropic shape [22]. In the limit $|a| \gg a_r$, the binding energy takes the universal form $E_B \approx 0.6\hbar\omega_r$ and for positive a and $a \ll a_r$ the usual 3D expression for the binding energy $E_B = \hbar^2/ma^2$ is recovered.

A trapped gas is kinematically one-dimensional if both the chemical potential and the temperature are smaller than the level spacing due to the transverse confinement. For a harmonically trapped Fermi gas the Fermi energy $E_F = N \cdot \hbar\omega_z$ must be smaller than the energy gap to the first excited state in the transverse direction $\hbar\omega_r$. N denotes the number of particles and ω_z is the trapping frequency along the weakly confining axis. In our experiment we employ a two-dimensional optical lattice in order to create 1D Fermi gases. For atoms trapped in the intensity maxima of the two perpendicular standing wave laser fields, the radial confinement is only a fraction of the optical lattice period [23]. The much weaker axial trapping is a consequence of the Gaussian intensity envelope of the lattice laser beams. The resulting aspect ratio $\frac{\omega_r}{\omega_z} = \frac{\pi w}{\lambda}$ is determined by the waist w and the wavelength λ of the beams. The two-dimensional optical lattice creates an array of 1D tubes of which approximately 70×70 are occupied [24]. This array fulfills the 1D condition $N < \omega_r/\omega_z \approx 270$ in each tube while simultaneously providing a good imaging quality.

One-dimensional quantum systems have been realized with fermions in, e.g., semiconductor nanostructures [25], and with bosons in ultracold atomic gases [18–21,26] but so far the scattering length could not be tuned. Here we overcome this by using a magnetic field induced Feshbach resonance between two different spin states of the atoms. The resonance is characterized by its position B_0, its width ΔB, and the background scattering length $a_{\rm bg}$. The scattering length varies according to $a(B) = a_{\rm bg}(1 - \frac{\Delta B}{B - B_0})$ which allows us to access any value of the scattering length and study the predicted bound states in 1D.

Our experimental procedure used to produce a degenerate Fermi gas trapped in an optical lattice has been described in detail in previous work [27]. Fermionic ^{40}K atoms are sympathetically cooled by thermal contact with bosonic ^{87}Rb atoms, the latter being subjected to forced microwave evaporation. After reaching quantum degeneracy for both species with typically 6×10^5 potassium atoms at a temperature of $T/T_F = 0.35$ (T_F is the Fermi temperature), we remove all rubidium atoms from the trap. The potassium atoms are then transferred from the magnetic trap into a crossed-beam optical dipole trap where we prepare a spin mixture with $(50 \pm 2)\%$ in each of the $|F = 9/2, m_F = -9/2\rangle$ and $|F = 9/2, m_F = -7/2\rangle$ spin states using a sequence of two radio-frequency pulses. From now on we will refer to the atomic state only with its respective m_F number. By lowering the optical trap depth at a magnetic field of $B = 227$ G, which is well above the magnetic Feshbach resonance centered at $B_0 = 202.1$ G [28], we evaporatively cool the potassium cloud to a temperature of $T/T_F = 0.2$ with 1.5×10^5 particles.

Prior to loading the atoms into the optical lattice we tune the magnetic field to $B = 210$ G, so that the s-wave scattering length between the two states vanishes. The magnetic field strength is calibrated by radio-frequency spectroscopy between different Zeeman levels of ^{40}K and the uncertainty is below 0.1 G. The process of loading the atoms from an optical dipole trap made up from crossing beams along the horizontal x and y axes into a two-dimensional lattice consisting of two standing waves along the y and z axes proceeds as follows: first the standing wave laser field along the vertical z axis is turned on. Subsequently, the optical dipole trap along the y axis is turned off and a standing wave laser field along the same axis is turned on. Finally, the optical trap along the x axis is turned off. In order to keep the loading of the atoms into the lattice as adiabatic as possible, the intensities of the lasers are slowly increased (decreased) using exponential ramps with time constants of 10 ms (25 ms) and durations of 20 ms (50 ms), respectively. The optical dipole trap and the lattice are created using the same laser beams which are focused to $1/e^2$ radii of 50 μm (x axis) and 70 μm (y axis and z axis) and have a wavelength of $\lambda = 826$ nm. They possess mutually orthogonal polarizations and their frequencies are offset with respect to each other by several tens of MHz. The optical potential depth is proportional to the laser intensity and is conveniently expressed in terms of the recoil energy $E_r = \hbar^2 k^2/(2m)$, with $k = 2\pi/\lambda$. The lattice depth was calibrated by intensity modulation and studying the parametric heating. The calibration error is estimated to be $<10\%$.

We create molecules by ramping the magnetic field from the zero crossing of the scattering length at $B = 210$ G in 10 ms to its desired value close to the Feshbach resonance. Depending on the final value of this sweep, the binding energy of the molecules varies according to Eq. (1). We measure the binding energy E_B of the dimers by radio-frequency spectroscopy [3]. A pulse with a frequency $\nu_{\rm rf}$ and a duration of 40 μs dissociates the molecules and transfers atoms into the initially unpopulated $|-5/2\rangle$ state which does not exhibit a Feshbach resonance with the state $|-9/2\rangle$ at this magnetic field. We vary the detuning $\delta = \nu_{\rm rf} - \nu_0$ from the resonance frequency ν_0 of the atomic $|-7/2\rangle \rightarrow |-5/2\rangle$ transition. The power and duration of the pulse is optimized to constitute a π pulse on the free atom transition. The number of atoms in each spin state is detected using absorption imaging after ballistic expansion. For this we ramp down the lattice exponentially with a duration of 1 ms and time constant of 0.5 ms from the initial depth V_0 to $5E_r$ to reduce the kinetic energy of the gas in the transverse directions and then quickly turn off the trapping potential. The magnetic offset field is

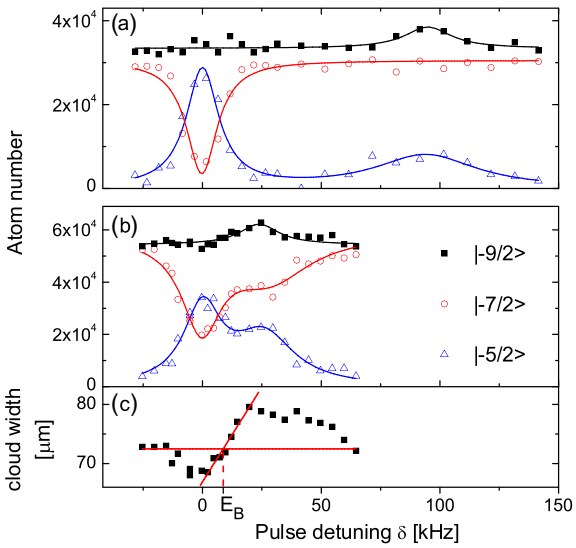

FIG. 1 (color online). Radio-frequency (rf) spectroscopy of a one-dimensional gas at magnetic fields 201.5 G (a) and 203.1 G (b), (c) with respective scattering lengths $(2.5 \times 10^3)a_0$ (a) and $(-1.2 \times 10^3)a_0$ (b), (c), where a_0 is the Bohr radius. The atom number in the respective spin states is plotted vs the detuning of the applied rf pulse in (a) and (b). The solid lines are single or double Lorentzian fits. (c) Width of the $|-9/2\rangle$ atom cloud along the 1D tube direction after 7 ms time of flight obtained from a fit [39] to the atomic density distribution. The horizontal line marks the average width for an off-resonant rf pulse; the increase at the molecule dissociation threshold is fitted using a linear function. The decrease in width at higher detunings is due to a diminishing dissociation efficiency.

switched off at the start of the expansion, so that no molecules can be formed in the short time that it passes the Feshbach resonance. We apply a magnetic field gradient during 3 ms of the total 7 ms of ballistic expansion to spatially separate the spin components.

Figure 1 shows rf spectra for one-dimensional gases with a potential depth of the optical lattice of $V_0 = 25E_r$, which corresponds to $\omega_r = 2\pi \times 69$ kHz. In Fig. 1(a) the magnetic field is detuned 0.57 G below the Feshbach resonance, i.e., $a > 0$. This spectrum exhibits two resonances: one corresponds to the $|-7/2\rangle \rightarrow |-5/2\rangle$ transition for free atoms at $\delta = 0$; the other at $\delta > 0$ corresponds to dissociated molecules. The constituent atoms of the dimers are observed in the $|-9/2\rangle$ and $|-5/2\rangle$ states. At this magnetic field, the molecules are not detected by our state-selective imaging procedure unless the are dissociated by an rf pulse. This is due to the fact that they are transformed into deeply bound molecules during the switch-off of the magnetic field.

In Fig. 1(b) the magnetic field is chosen 0.95 G above the resonance, i.e., $a < 0$. Again, the appearance of a second peak in the $|-5/2\rangle$ atom number at $\delta > 0$ demonstrates the existence of a bound state in our 1D geometry. These bound states are confinement induced since no molecules exist without confinement above the Feshbach resonance. They are only stabilized by the presence of the confining potential. Ramping down the lattice before detection dissociates the dimers and therefore all atoms should be detected in the image and the total particle number is expected to remain constant. This is reflected in our data, where the $|-7/2\rangle$ atom number decreases upon dissociation while the $|-5/2\rangle$ atom number increases. The slightly smaller total particle number away from the molecular resonance could be due to a small fraction of molecules formed during the switch-off of the magnetic field. Moreover, reduced losses of the rf dissociated atom pairs with respect to molecules during the 1 ms lattice turn-off might be held responsible.

The rf pulse not only breaks the pairs if the detuning δ exceeds the binding energy E_B, but also imparts the kinetic energy $\Delta E = 2\pi\hbar\delta - E_B$ to the fragments. In the 1D tubes only the kinetic energy along the tube axis increases as the motion in the other direction is frozen out for $\Delta E < \hbar\omega_r$. The cloud width shown in Fig. 1(c) is extracted from the momentum distribution obtained from time-of-flight images. We use this characteristic to determine the binding energy. This is done by identifying the threshold position at which the cloud width exceeds that of a cloud without dissociation. The latter is determined by the Fermi statistics of the trapped atoms and the interaction of the $|-9/2\rangle$ with the $|-7/2\rangle$ atoms close to the Feshbach resonance. The decrease at $\delta \approx 0$ is due to the particle transfer into the $|-5/2\rangle$ state and an accordingly weaker interaction energy. Owing to this complication and possible collisional shifts [29,30] we estimate the systematic error of our binding energy measurements in all data sets to be 10 kHz.

We have investigated the dependence of the binding energy of the 1D dimers on the magnetic field (Fig. 2) and we observed bound states for every examined magnetic field strength. The dimers at magnetic fields above the Feshbach resonance are induced by the confinement. The data are in good agreement with the theoretical expectation calculated from Eq. (1) (solid line) with no free parameters. For this calculation we compute the effective harmonic oscillator length a_r and the ground state energy $\hbar\omega_r$ by minimizing the energy of a Gaussian trial wave function in a single well of the lattice to account for the anharmonicity of the potential. To calculate the scattering length we use a width of the Feshbach resonance of $\Delta B = 7.8$ G [31] and background scattering length $a_{\mathrm{bg}} = 174a_0$ [32].

For a comparison with the situation in free space we created molecules in a crossed-beam optical dipole trap without optical lattice where confinement effects are not relevant. The binding energy in 3D is measured with the same rf spectroscopy technique as for the 1D gas and we find molecules only for scattering lengths $a > 0$. The binding energy is calculated according to [33] as $E_{B,3D} = \frac{\hbar^2}{m(a-\bar{a})^2}$, with $\bar{a} = (mC_6/\hbar^2)^{1/4}\frac{\Gamma(3/4)}{2\sqrt{2}\Gamma(5/4)}$ being the effective scattering length and $C_6 = 3897$ (in atomic units) [34]. The deviation of the theory from the measured data for more deeply bound molecules is probably due to limitations of this single channel theory. A multichannel calculation would determine the binding energy more accurately.

Exactly on the Feshbach resonance where the scattering length diverges, the binding energy takes the universal form $E_B \approx 0.6\hbar\omega_r$ and is solely dependent on the external confinement. We have varied the potential depth of the optical lattice and thereby the transverse confinement and

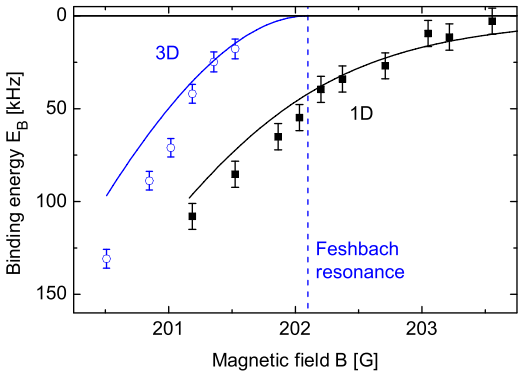

FIG. 2 (color online). 1D and 3D molecules. Confinement induced molecules in the 1D geometry exist for arbitrary sign of the scattering length. The solid lines show the theoretical prediction of the binding energy with no free parameters (see text). In the 3D case, we observed no bound states at magnetic fields above the Feshbach resonance (vertical dashed line). The error bars reflect the uncertainty in determining the position of the dissociation threshold.

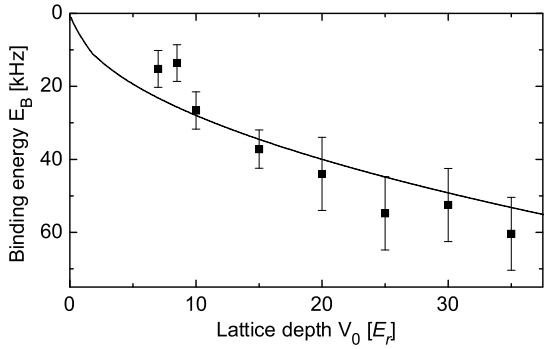

FIG. 3. Changing the confinement. The spectra are taken very close to the Feshbach resonance at a magnetic field of $B = 202.0$ G. The binding energy is measured by rf spectroscopy. For $V_0 \geq 30E_r$ no increase in kinetic energy could be detected and we used the rising edge in the $|-5/2\rangle$ atom number in the spectrum to determine the binding energy. The error bars reflect the uncertainty in determining the position of the dissociation threshold. The solid line shows the theoretically expected value.

measured the binding energy. We find good agreement of our data with the theoretical prediction (see Fig. 3). For a very low depth of the optical lattice the measured data deviate from the 1D theory due to the fact that the gas is not one-dimensional anymore.

In conclusion, we have realized an interacting 1D Fermi gas in a two-dimensional optical lattice. Using a Feshbach resonance we have created molecules and measured their binding energy. We find two-particle bound states for arbitrary sign of the scattering length, which, in the case of negative scattering length, are stabilized only by the tight transverse confinement. We find good agreement with theory describing the two-particle physics. The strongly interacting 1D Fermi gas realizes an atomic Luttinger liquid, and fascinating many-body phenomena are predicted in this system [35–37]. Especially intriguing appears the BCS-BEC crossover for which exactly solvable models exist in one dimension [22,38].

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