p-Wave Interactions in Low-Dimensional Fermionic Gases

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(Received 26 July 2005; published 28 November 2005)

We study a spin-polarized degenerate Fermi gas interacting via a *p*-wave Feshbach resonance in an optical lattice. The strong confinement available in this system allows us to realize one- and two-dimensional gases and, therefore, to restrict the asymptotic scattering states of atomic collisions. When aligning the atomic spins along (or perpendicular to) the axis of motion in a one-dimensional gas, scattering into channels with the projection of the angular momentum of $|m| = 1$ (or $m = 0$) can be inhibited. In two and three dimensions, we observe the doublet structure of the *p*-wave Feshbach resonance. For both the one-dimensional and the two-dimensional gases, we find a shift of the position of the resonance with increasing confinement due to the change in collisional energy. In a three-dimensional optical lattice, the losses on the Feshbach resonance are completely suppressed.

Ultracold fermionic atoms constitute a well controllable many-particle quantum system which provides access to fundamental concepts in physics. Using optical lattices, the atomic motion and the dimensionality of the trapping geometry can be controlled. Yet, it is the collisional interaction between atoms which provides the avenue towards the physical richness of the strongly correlated regime [1–4]. Particularly intriguing are *p*-wave collisions due to their anisotropic character. These can be experimentally accessed exploiting a Feshbach resonance which overcomes the suppression of the collisional cross section at ultralow energies [5–7].

In this Letter, we prepare a spin-polarized Fermi gas in an optical lattice and investigate *p*-wave collisions in the vicinity of a Feshbach resonance controlled by the magnetic field. We study the resonant behavior of the atom losses as a function of the magnetic field and observe distinct features depending on the dimensionality and the symmetry of the system. For a three-dimensional gas, a double-peaked structure appears, as has previously been reported by Ticknor *et al.* [8]. This characteristic survives when the dimensionality is reduced to two dimensions (2D) but appears shifted in magnetic field. For one-dimensional (1D) geometries, only a single shifted resonance peak is observed. All resonantly enhanced losses vanish when the spin-polarized gas is loaded into the lowest band of a three-dimensional optical lattice, in which each site can be regarded as a system of "zero dimensions."

These observations can be qualitatively explained by considering the symmetry of the collisions, as illustrated in Fig. 1. The external magnetic field orients the polarization of the atoms and its direction may be chosen as the quantization axis. In order to describe the atom-atom scattering with *p*-wave symmetry, the angular part of the corresponding asymptotic wave functions can be expressed in terms of spherical harmonics. Alignment of the scattering state parallel to the quantization axis corresponds to the spherical harmonic $Y_{\ell=1,m=0}$, and alignment in the plane

perpendicular to the quantization axis corresponds to superpositions of the spherical harmonics $Y_{\ell=1,m=\pm1}$. The dipole-dipole interaction between the electronic spins lifts the degeneracy between the $|m| = 1$ and the $m = 0$ collisional channels which leads to a splitting of the Feshbach resonance [8]. In the two- and three-dimensional configurations, both collisional channels are present, giving rise to the observed doublet feature [see Figs. 2(a) and 2(b)]. In one dimension, with the spin aligned orthogonal or parallel to the atomic motion, either the $|m| = 1$ [see Fig. 2(c)] or the $m = 0$ [see Fig. 2(d)] collisional channel is contributing, leading to a single peak. In zero dimensions—as
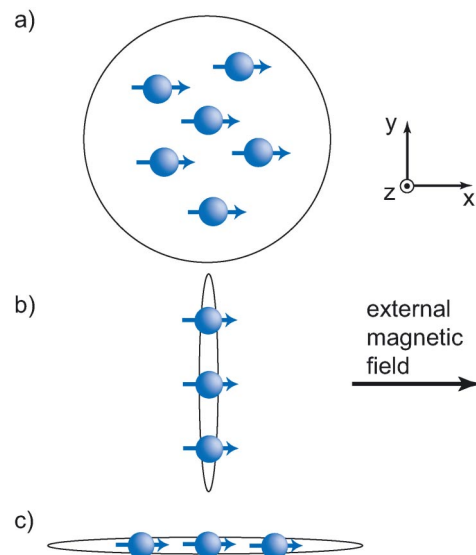

FIG. 1 (color online). Spin-alignment dependent interactions in 1D and 2D. In the two-dimensional configuration of (a), all projections of the angular momentum in the *p*-wave collision are allowed. (b) and (c) show a one-dimensional spin-polarized Fermi gas with the spins aligned orthogonal and parallel to the extension of the gas, respectively. In (b), only the $|m| = 1$ projection of the *p*-wave contributes to the scattering, in (c) only the $m = 0$ projection.
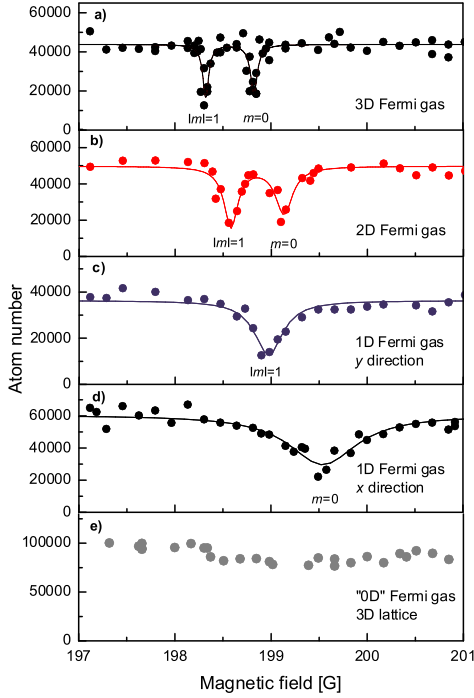
FIG. 2 (color online). Loss measurements of the p-wave Feshbach resonance. (a) Atoms are held in a crossed-beam optical dipole trap. (b) Two-dimensional Fermi gas ($V_z = 25E_r$). (c) One-dimensional Fermi gas with the motion confined orthogonal to the direction of the magnetic field ($V_z = V_x = 25E_r$). (d) One-dimensional Fermi gas with the motion confined parallel to the direction of the magnetic field ($V_z = V_y = 25E_r$). (e) Fermi gas in a three-dimensional optical lattice ($V_x = V_y = V_z = 25E_r$). The solid lines are Lorentzian fits to the data from which we extract the position and the width of the resonance.

realized in a three-dimensional optical lattice—p-wave collisions and the corresponding losses are absent [see Fig. 2(e)]. In these low-dimensional systems, the asymptotic scattering states are kinematically restricted. However, the atomic collision process is still three-dimensional, since the size of the ground state is large compared to the range of the interatomic potentials. Hence, the strongly confined directions can contribute to the collision energy [9].

One- and two-dimensional fermionic quantum systems have been realized in semiconductor nanostructures [10] and recently with noninteracting [11] and interacting [12,13] atomic gases in optical lattices. In these systems, the strong confinement modifies the scattering properties of the particles: It stabilizes molecular states and shifts the position of Feshbach resonances. This has been predicted for one- [14,15] and two-dimensional systems [16,17] interacting via s-wave scattering, and confinement induced molecules have been observed in a 1D gas [13]. Similarly, for spin-polarized fermions in one dimension, a confinement induced shift of p-wave Feshbach resonances is predicted [18].

Our experimental procedure used to produce a degenerate Fermi gas has been described in detail in previous work

[4]. 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 in the $|F = 9/2, m_F = 9/2\rangle$ hyperfine state 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 an optical dipole trap consisting of two intersecting laser beams along the horizontal x and y directions. These laser beams are derived from diode lasers at a wavelength of $\lambda = 826$ nm and are focused to $1/e^2$ radii of 50 μm (x axis) and 70 μm (y axis). In the optical trap, we prepare the atoms in the $|F = 9/2, m_F = -7/2\rangle$ spin state at a magnetic bias field of 232.9 G using two radio frequency (rf) sweeps. To remove residual atoms in the $|F = 9/2, m_F = -9/2\rangle$ state, we change the magnetic field in 100 ms to a value of 201.7 G, close to the s-wave Feshbach resonance between $|F = 9/2, m_F = -9/2\rangle$ and $|F = 9/2, m_F = -7/2\rangle$ [5,13], where we encounter inelastic losses resulting in a pure spin-polarized Fermi gas. Subsequently, we increase the magnetic field within 100 ms to 203.7 G. Then we evaporate atoms by lowering the optical trapping potential during 2.5 s to a final value of $7E_r$ in each of the two beams, where $E_r = \hbar^2 k^2/(2m_K)$ denotes the recoil energy, $k = 2\pi/\lambda$ the wave vector of the laser, and m_K the atomic mass. The preparation of the gas is completed by rapidly (< 1 ms) decreasing the magnetic field to 194.4 G, which is below the p-wave Feshbach resonance. We have calibrated the magnetic field by rf spectroscopy between Zeeman levels with an accuracy better than 100 mG, and we estimate the reproducibility of our magnetic fields to be better than 50 mG.

For comparison with the low-dimensional situations, we first study the p-wave Feshbach resonance in the crossed-beam optical trap where motion in all three dimensions is possible. We sweep the magnetic field from its initial value of 194.4 G using a linear ramp within 1 ms to its final value in the vicinity of the Feshbach resonance. There the atoms are subject to inelastic losses [5]. After a hold time of 6.4 ms, we switch off both the magnetic field and the optical trap and let the atomic cloud expand ballistically for 7 ms before we take an absorption image. From the image, we extract the remaining number of atoms. In these data [see Fig. 2(a)], we observe the doublet structure of the p-wave Feshbach resonance, which is due to magnetic dipole-dipole interactions between the atoms [8]. The decay constant of the atom number close to the Feshbach resonance is on the order of 1 ms, which is comparable to the settling time of the magnetic field. Therefore, we encounter a systematic shift on the order of $+0.1$ G due to the direction of the magnetic field ramp [19].

In a next step, we additionally apply a single optical standing wave along the vertical z axis. The standing wave with a potential depth V_z [20] creates a stack of two-dimensional Fermi gases in the horizontal x-y plane. The lattice laser intensity is increased using an exponential

ramp with a time constant of 10 ms and a duration of 20 ms. The beam for the vertical optical lattice is derived from a diode laser at a wavelength of $\lambda = 826$ nm and is focused to a $1/e^2$ radius of 70 μm. The magnetic field is aligned along the horizontal x axis, as depicted in Fig. 1(a). In the two-dimensional Fermi gas, we have studied the p-wave Feshbach resonance analogous to the method described above, only the release process of the atoms is slightly altered: Within 1 ms before the simultaneous switch-off of the magnetic and the optical potentials, we lower the lattice intensity to $V_z = 5E_r$ to reduce the kinetic energy. This results in a more isotropic expansion which allows one to determine the atom number more precisely.

For the two-dimensional gas, we observe a similar doublet structure of the Feshbach resonance but shifted towards higher magnetic field values with respect to the position without strong confinement [see Fig. 2(b)]. Because of the angular momentum in a p-wave collision, there is a centrifugal barrier in addition to the interatomic potential, which results in a pronounced energy dependence of the scattering. In the confined gas, the collision energy is modified by the motional ground state energy and the larger Fermi energy of the gas due to the confinement. Moreover, a confinement induced shift of the resonance could be envisaged, similar to what has been studied for s-wave interactions in two dimensions [16,17].

We experimentally find that the shift of the resonance feature depends on the strength of the optical lattice. In Fig. 3, we compare the measured shift with a model in which we set the collision energy of the particles to be the Fermi energy plus the ground state energy. We numerically calculate the Fermi energy for the noninteracting gas in the full three-dimensional configuration of the optical lattice and the harmonic confining potential. We use a tight-binding model for the direction of the lattice laser and a harmonic oscillator potential in the transverse directions. Using the parametrization of the Feshbach reso-
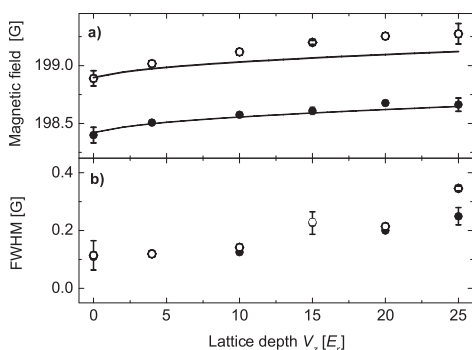

FIG. 3.   (a) Shift of the Feshbach resonance position when tuning the gas from three to two dimensions. Open symbols indicate the position of the $m = 0$ branch, solid symbols the $|m| = 1$ branch of the resonance. The error bars denote the statistical error of 3 measurements. The solid lines show a calculation of the expected positions (see text). (b) Evolution of the full width at half maximum (FWHM) of the loss feature.

nance according to Ref. [8], we obtain the shifted position of the resonance for a given lattice depth. For the $|m| = 1$ branch of the resonance, we find good agreement of our data with the theory, whereas, for the $m = 0$ branch, the observed shift is larger than predicted by our model. There may be an additional confinement induced shift of the p-wave resonance which depends on the m-quantum numbers in the collision process [18]; however, no quantitative theory is available. The observed increasing width of the Feshbach resonance is also due to a larger collision energy [8].

Reducing the dimensionality further, we study the effect of the alignment of the electronic spins on the p-wave interaction in a one-dimensional quantum gas. Therefore, all spins are lined up either orthogonal [see Fig. 1(b)] or parallel [Fig. 1(c)] to the orientation of the gas. We prepare the one-dimensional Fermi gases by superimposing a second standing wave laser field onto the two-dimensional quantum gases [13]. Either the x or the y direction of the optical dipole trap is slowly turned off and replaced by an optical lattice along the same direction and having the same beam geometry.

We now consider the orthogonal configuration where only collisions with $|m| = 1$ are possible, and, correspondingly, we observe only this branch of the Feshbach resonance [see Fig. 2(c)]. To study the suppression of the $m = 0$ branch quantitatively, we create a two-dimensional optical lattice along the x and the z direction with $V_z = 25E_r$ and adjustable V_x. We have measured the peak loss on the $m = 0$ and the $|m| = 1$ resonance position, respectively. In Fig. 4(a), we plot the ratio of the peak loss versus the tunneling matrix element along the x direction, i.e., between the tubes of the optical lattice. For no tunneling, the one-dimensional gases are well isolated and losses on the $m = 0$ branch are completely suppressed. For larger tunneling rates, hopping of atoms between the tubes is possible, and the system is not kinematically one-dimensional any more but in a crossover regime. Therefore, collisions in the $m = 0$ branch become possible which give rise to losses. The measurement directly verifies suppressed tunneling between neighboring lattice tubes and proves that the gases in the individual lattice tubes are kinematically one-dimensional. Orienting the one-dimensional quantum gases parallel to the magnetic field axis, we observe the $m = 0$ branch of the Feshbach resonance only [see Fig. 2(d)]. Note that the width and the position of crossover regime is determined by the time scale of the physical processes under investigation: In this Letter, we are one-dimensional with respect to atomic collision time scales but not necessarily for slower dynamical processes such as collective oscillations [21].

For the one-dimensional Fermi gases, we observe a further shift of the resonance position and a broadening of the loss feature as compared to the higher-dimensional configurations. A confinement induced shift of the p-wave resonance in one dimension for the $m = 0$ branch has been predicted in addition to the increased ground state and
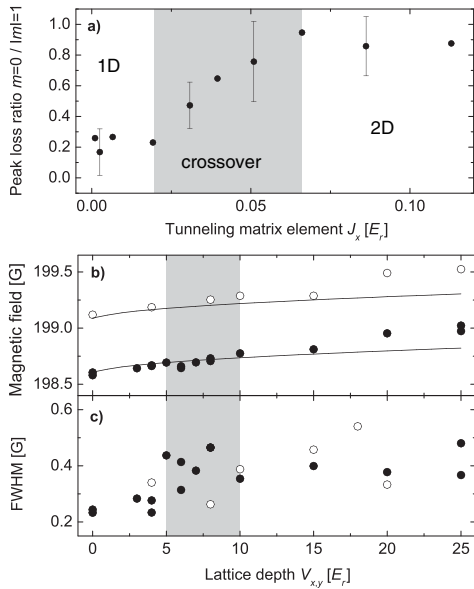
FIG. 4. (a) Suppression of collisional losses in the $m = 0$ partial wave versus the tunneling matrix element between the one-dimensional quantum gases. The bars reflect the errors determined from the fit to the loss peaks of two measurements. The gray box indicates the crossover region from a 2D to a 1D quantum gas as inferred from the inhibition of transverse collisions. (b) Shift of the position of the Feshbach resonance when tuning the gas from 2D to 1D. Open symbols indicate the position of the $m = 0$ branch in the y-z lattice [see Fig. 1(c)] and the solid symbols the $|m| = 1$ branch of the resonance in the x-z lattice [see Fig. 1(b)]. The solid lines show a calculation of the expected positions (see text). (c) Width of the Feshbach resonance loss feature.

Fermi energy [18]. We apply the calculation technique as described above to obtain the Fermi energy of the gas and use the same parametrization of the Feshbach resonance. For the $m = 0$ branch, we additionally include the theory of Ref. [18] for all lattice depths. This introduces a small error in the 2D and crossover regime. We note, however, that the confinement induced shift is small as compared to the shift due to the increased collision energy. A comparison between the resulting shift and the experimental data is shown in Fig. 4(b). The increasing width of the loss feature is expected because the width of the Feshbach resonance also depends on the energy of the particles involved in the collision process [8].

By using three orthogonal standing waves, we prepare a band-insulating state in a 3D optical lattice [4] where the atoms are localized in the potential wells with, at most, one atom per lattice site. In this "zero-dimensional" situation, all p-wave scattering is completely inhibited [see Fig. 2(e)] and no loss features are observed.

In conclusion, we have studied spin-polarized interacting Fermi gases in low dimensions using a p-wave Feshbach resonance. We demonstrate that, in reduced dimensions, the direction of spin-alignment significantly influences the scattering properties of the particles. Moreover, we find a confinement induced shift of the resonance position and observe good agreement with a theoretical model. Strongly interacting low-dimensional Fermi gases offer a wealth of fascinating many-body phenomena [22].

We thank D. Blume for discussions and SNF and SEP Information Sciences for funding.

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