Magnetic Field Control of Elastic Scattering in a Cold Gas of Fermionic Lithium Atoms

S. Jochim, M. Bartenstein, G. Hendl, J. Hecker Denschlag, and R. Grimm
Institut für Experimentalphysik, Universität Innsbruck, Technikerstrasse 25, 6020 Innsbruck, Austria

A. Mosk
FOM instituut voor plasmafysica Rijnhuizen, P.O. Box 1207, 3430 BE Nieuwegein, The Netherlands

M. Weidemüller
Max-Planck-Institut für Kernphysik, Postfach 103980, 69029 Heidelberg, Germany
(Received 24 July 2002; published 18 December 2002)

We study elastic collisions in an optically trapped spin mixture of fermionic lithium atoms in the presence of magnetic fields up to 1.5 kG by measuring evaporative loss. Our experiments confirm the expected magnetic tunability of the scattering length by showing the main features of elastic scattering according to recent calculations. We measure the zero crossing of the scattering length at 530(3) G which is associated with a predicted Feshbach resonance at ~850 G. Beyond the resonance we observe the expected large cross section in the triplet scattering regime.

DOI: 10.1103/PhysRevLett.89.273202 PACS numbers: 34.50.–s, 05.30.Fk, 32.80.Pj, 39.25.+k

In an ultracold atomic gas, the *s*-wave scattering length characterizes the elastic interactions and has a profound effect on the physical behavior. The scattering length can be conveniently tuned by using a magnetic field when a Feshbach resonance is present. For bosonic atoms, such resonances have been observed [1–3], and they have found particular applications for attainment and manipulation of a Bose-Einstein condensate in ^{85}Rb [4,5] and for the production of bright solitons in bosonic ^{7}Li [6,7].

For fermionic gases, Feshbach resonances in *s*-wave scattering of atoms in different spin states are of great interest to experimentally explore the rich physics of paired fermionic gases [8–11]. For obtaining superfluidity in a Cooper-paired gas, magnetic tuning allows one to raise the critical temperature [8] from values far below the Fermi temperature into a region that seems accessible with current experimental methods. With resonantly tuned interactions the fermionic superfluid is predicted [9,10] to perform a crossover from a superfluid of weakly coupled Cooper pairs to a Bose-Einstein condensate of strongly coupled molecules. Feshbach tuning also offers a possible way to detect this molecular coupling through oscillations induced by magnetic-field transients [10] analogous to a recent observation with coupled bosonic atoms [5]. Experimental control of different pairing regimes thus represents an intriguing prospect of a fermionic gas with magnetically tuned interactions.

A narrow Feshbach resonance between two different spin states of fermionic ^{40}K was recently observed by Loftus *et al.* [12]. The other fermionic species currently used in several experiments, ^{6}Li, is predicted to a show a Feshbach resonance with strong modifications of *s*-wave interactions in a very wide magnetic-field range [13–15]. At relatively small fields, this dependence was recently used by Granade *et al.* to obtain a sufficient scattering cross section for the all-optical production of a degenerate Fermi gas of lithium [16].

In this Letter, we experimentally explore the magnetic tunability of elastic scattering in an optically trapped spin mixture of fermionic lithium atoms in high magnetic fields up to 1.5 kG. Our results verify the expected dependence of *s*-wave interactions in the whole magnetic-field range of interest [13–15]. As a particular feature associated with the predicted Feshbach resonance [13], we observe the zero crossing of the scattering length at a field of 530 G. The exact location of this feature is of great interest as a sensitive input parameter to better constrain the uncertainty in the molecular potentials for more accurate theoretical calculations of the scattering properties of ^{6}Li. Our measurements of elastic collisions are based on evaporation out of an optical dipole trap.

The scattering properties in different spin mixtures of fermionic lithium atoms were theoretically investigated by Houbiers *et al.* [13], Kokkelmans *et al.* [14], and Venturi and Williams [15]. Magnetic tunability, of particular interest for Cooper pairing in a Fermi gas [8,9], was predicted for the stable combination of the two lowest states $|1\rangle$ and $|2\rangle$; at low magnetic field these states correspond to $F = 1/2$, $m_F = +1/2$, and $m_F = -1/2$, respectively. Most prominently, a broad Feshbach resonance at ~850 G is expected to mark the transition from the low-field scattering regime to the high-field region. As a precursor of the Feshbach resonance, the *s*-wave scattering length a crosses zero in the range between 500 and 550 G. Beyond the resonance, scattering in higher fields is dominated by the triplet potential with a very large and negative scattering length of $-2200a_0$, where a_0 is the Bohr radius. The available theoretical data [13–15] show the same behavior for $a(B)$ within some variations due to the limited knowledge of the

molecular interaction parameters. Figure 1(a) illustrates these predictions for the scattering length $a(B)$ by a corresponding model curve that approximates the results of Refs. [13–15].

In a cold gas at finite temperature the cross section for elastic scattering of nonidentical particles is unitarity limited to a maximum value of $\sigma_{\max} = 4\pi/k^2$, where $k = m\upsilon/(2\hbar)$ is the wave number corresponding to a relative velocity υ and a reduced mass $m/2$. Taking into account the B-field dependent scattering length $a(B)$ and the unitarity limit, the resulting B-field dependent cross section can be written as $\sigma = 4\pi a^2/(1 + k^2a^2)$. For the considered $|1\rangle - |2\rangle$ spin mixture of ^{6}Li the expected behavior of the cross section is shown in Fig. 1(b) for the example of a wave number $k = (300a_0)^{-1}$ close to our experimental conditions. Most notably, as a consequence of the unitarity limit in combination with the very large scattering length for high magnetic fields, the Feshbach resonance does not appear as a pronounced feature in the cross section. The zero crossing of the scattering length, however, leads to a vanishing scattering cross section and thus shows up as a manifestation of the resonance.

Our dipole trap [17] makes use of the enhancement of the laser intensity inside a linear optical resonator to create a large and deep trapping volume for lithium atoms. The power provided by a 2-W Nd:YAG laser (Innolight Mephisto-2000) at a wavelength of 1064 nm is enhanced by a factor of 120 to create a far red-detuned 1D optical lattice trap with an axial period of 532 nm and a transverse $1/e$ radius of 115 μm. The maximum trap depth is of the order of 1 mK. To vary the trap depth the resonator-internal power is servo-controlled by an acousto-optical modulator in the incident laser beam. From a standard magneto-optical trap (MOT) operated with diode lasers we typically transfer 5×10^5 ^{6}Li atoms into roughly 1000 individual wells at a temperature of

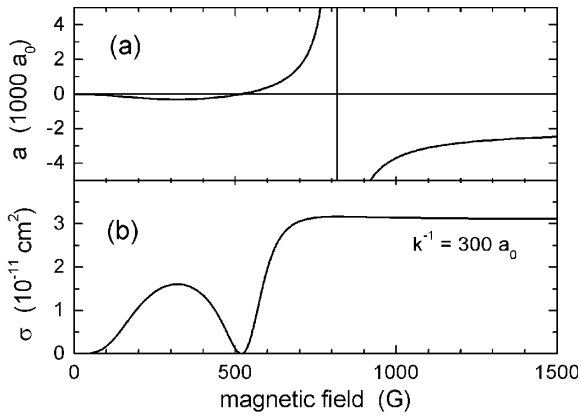

FIG. 1. (a) Model curve approximating the results of [13–15] for the s-wave scattering length of ^{6}Li atoms in the two lowest spin states versus magnetic field. (b) Corresponding behavior of the scattering cross section at a finite collision energy with a relative wave number of $k = (300a_0)^{-1}$.

$\sim$400 μK. The resulting peak density is $\sim 1.5 \times 10^{11}$ cm^{-3}. By extinguishing the repumping light of the MOT 1 ms before the main trapping light is turned off, all atoms are pumped into the two states $|1\rangle$ and $|2\rangle$ to create a 50-50 spin mixture [16].

The magnetic field is produced by a pair of water-cooled coils outside of the glass vacuum cell of the trap. At a maximum continuous operation current of 200 A the coils produce a magnetic field of 1.5 kG with a curvature of only 75 G/cm^2 along the symmetry axis; the corresponding power dissipation is 6 kW. The setup allows for a maximum ramp speed of 5 G/ms within the full range. The magnetic field is calibrated by radio-frequency induced transitions from $|2\rangle$ to the state that at $B = 0$ corresponds to $F = 3/2$, $m_F = +1/2$. The latter is unstable against inelastic collisions with $|2\rangle$ which leads to easily detectable loss. With a fit to the Breit-Rabi formula we obtain a calibration of the magnetic field to better than 1 G over the full range.

The basic idea of our measurements is to observe elastic collisions through evaporative loss at a variable magnetic field [18]. The method is particularly well suited for measuring the position of a resonance by locating the corresponding zero crossing of the scattering length. With this sensitive experimental input for theoretical calculations, as is readily available in our case [13–15], precise knowledge of the magnetic-field dependent scattering length can be obtained. Our dipole trap is loaded under conditions where the effective temperature T of a truncated Boltzmann distribution [19] is only slightly below the trap depth U. A strongly nonthermal distribution is thus created with a small truncation parameter $\eta = U/k_BT \approx 2$. The thermal relaxation resulting from elastic collisions then leads to rapid evaporative loss and cooling of the sample, i.e., an increase of η. The trap depth can be kept constant to study plain evaporation or, alternatively, ramped down to force the evaporation process.

In a series of plain evaporation experiments performed at a constant trap depth of 750 μK we measure evaporative loss over the maximum accessible range of magnetic fields up to 1.5 kG. After a fixed holding time the remaining atoms are retrapped into the MOT and their number is measured via the fluorescence signal by a calibrated photodiode. The signal is recorded after holding times of 1 and 3 s corresponding to the time scale of evaporation. These holding times are short compared with the rest-gas limited lifetime of 30 s. Figure 2 shows the result of 1000 different measurements obtained in an acquisition time of 6 h. The data points are taken in a random sequence for 31 magnetic field values equally distributed over the full range. Data points for 1 and 3 s are recorded alternatingly. This way of data taking ensures that the signal is not influenced by residual long-term drifts of the experimental conditions.

The observed evaporation loss in Fig. 2 shows a pronounced dependence on the magnetic field, which we

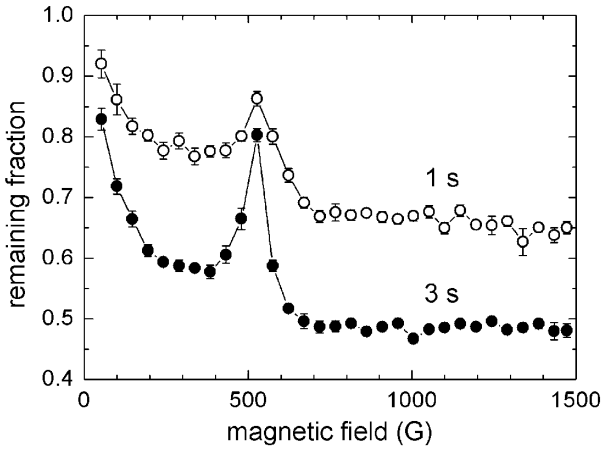

FIG. 2. Evaporative loss measurements over the full magnetic field range. The data points show the measured number of atoms remaining in the trap after 1 s (∘) and 3 s (•) of plain evaporation at a constant trap depth of 750 μK.

compare with the expected cross section for elastic collisions ejecting atoms out of the trap. Figure 1(b) displays the cross section for $k = (300a_0)^{-1}$, which corresponds to a collision energy of about half the trap depth and thus to the relevant energies for evaporating collisions. After being very small at low magnetic fields, the observed loss increases for fields up to ~350 G where the expected local maximum of evaporation shows up. The loss then decreases and disappears at about 530 G in agreement with the predicted zero crossing of the scattering length. Here the slight observed loss in the 1 s curve is explained by the finite ramp time of the magnetic field. In the 100 ms ramping time some evaporation does already take place. At 530 G the decrease of the trapped atom number between 1 and 3 s is fully explained by rest-gas losses without any further evaporation. For higher magnetic fields evaporative loss rapidly rises until it levels off at about 700 G. Up to the maximum attainable value of 1.5 kG high evaporation loss is observed. A slight decrease of the atom number for fields exceeding 1 kG occurs which we attribute to technical reasons; we observe an increasing noise for currents higher than ~130 A in the error signal of the resonator lock. The relatively large and constant evaporative loss for fields exceeding 700 G is consistent with the predicted behavior of the cross section.

The evaporative cooling effect is confirmed by measuring the change of the truncation parameter η after 3 s of trapping at selected values of the magnetic field. For thermometry we turn off the magnetic field to avoid further elastic collisions and adiabatically lower the trap depth in a 1-s exponential ramp. The fraction of remaining atoms as a function of the relative depth then provides a good measure of η. At the zero crossing at 530 G we observe only a slight increase of η to a value of 2.3(3) which is explained by the unavoidable evaporation during the magnetic-field ramps. At 340 G close to the local maximum of $|a|$ we find an increase of η to 4.2(3) as a clear evidence of evaporative cooling. At 720 G, i.e., in the case of a large positive scattering length, a higher value of 5.5(4) is measured showing deeper evaporative cooling. Essentially the same η of 5.3(4) is obtained at $B = 1290$ G where scattering takes place in the triplet-dominated regime with a very large negative scattering length.

We measure the minimum-loss feature in a closer range of magnetic fields to precisely determine the value of the magnetic field at which the zero crossing of scattering length occurs. The main data points in Fig. 3 are obtained with 500 individual measurements at a holding time of 3 s with the magnetic field randomly varied between 30 values in an interval between 370 and 670 G; the data shown in the inset are obtained with 1000 measurements in the very narrow range between 520 and 544 G. The results allow us to determine the B field for minimum evaporative loss, and thus the zero crossing of the scattering length to 530(3) G [20].

Forced evaporation measurements provide complementary data to plain evaporation and allow us to rule out a significant role of inelastic collisions. When the trap depth is ramped down, elastic collisions reduce trap loss in contrast to increased loss at constant trap depth. This can be understood by the spilling loss of energetic particles [19]: Without elastic collisions the most energetic particles are spilled out of the trap when its depth is reduced. With elastic collisions the evaporative cooling effect decreases the temperature and thus reduces the spilling loss.

In our forced evaporation measurements we reduce the trap depth in 10 s to 20% of its initial value in an exponential ramp and measure the number of remaining atoms; the results are displayed in Fig. 4. A minimum

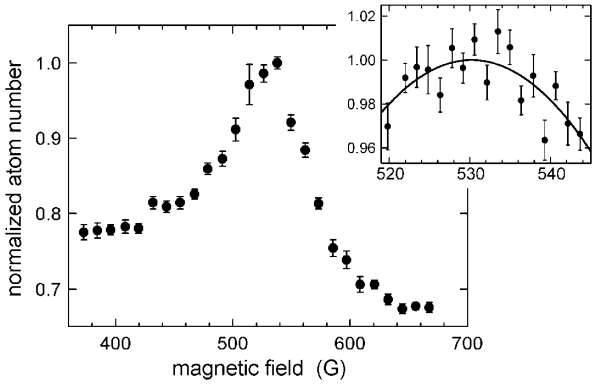

FIG. 3. Measurements on plain evaporation in magnetic fields close to the zero crossing of the scattering length under the same conditions as in Fig. 2 for a holding time of 3 s. Here the number of remaining atoms is normalized to the observed maximum value. The inset shows a series of measurements in a very narrow range around the maximum at 530(3) G together with a parabolic fit.

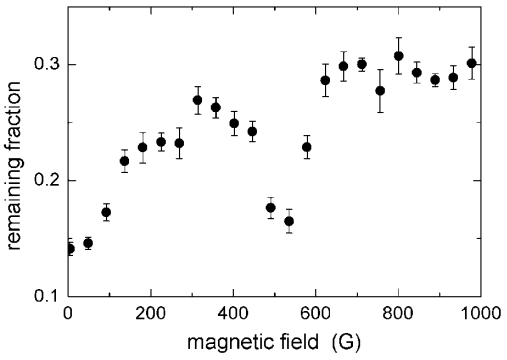

FIG. 4. Fraction of atoms remaining after forced evaporation versus applied magnetic field. The trap depth is ramped down exponentially in 10 s to 20% of the initial value.

number of atoms is now measured at 0 and 530 G instead of the maximum observed with constant trap depth. The largest number of atoms is observed in the high-field region above 650 G as expected for the large scattering cross section.

On a Feshbach resonance, enhanced inelastic loss can occur as a result of three-body collisions [1] or, if the system has internal energy, as a result of two-body decay [3]. For fermions, three-body processes are symmetry forbidden at ultralow energies when only s-wave collisions are involved. In a spin mixture at nonzero magnetic field, two-body decay is energetically possible (in our case with an energy release of $k_B \times 3.5$ mK) but involves higher partial waves and relies on weak dipolar coupling. Consequently, inelastic loss can be expected to be weak in our experiments. Indeed, our data do not show any indication of inelastic loss even at the very center of the Feshbach resonance.

At much higher densities ($\sim 10^{13}$ cm^{-3}) as compared to our conditions ($\sim 10^{11}$ cm^{-3}), a recent experiment [21] has revealed inelastic loss with a maximum at 680 G. As our results support the predicted position of the s-wave resonance at ~850 G, the explanation for the inelastic feature cannot be attributed to the Feshbach resonance in a simple way. The experiment [21] also provided evidence for a two-body nature of the underlying process with a rate constant of 2×10^{-12} cm^3/s measured at ~20 μK. At a higher temperature of ~100 μK we derive an upper bound for the two-body rate constant of 1×10^{-12} cm^3/s, whereas for a process involving higher partial waves one would expect the rate to increase with temperature. For three-body collisions our densities are too low to provide useful constraints. Obviously, inelastic loss in the fermionic spin mixture is an interesting problem that deserves more attention.

In conclusion, our measurements confirm the predicted magnetic tunability of the s-wave scattering length in a spin mixture of fermionic lithium atoms in the whole magnetic-field range of experimental interest. The observed zero crossing of the scattering length at 530(3) G together with the large cross section observed for higher fields provides clear evidence of the predicted Feshbach resonance. Moreover, it enables more precise calculations of the ^{6}Li scattering properties. The resonance itself is masked by unitarity-limited scattering and requires much deeper evaporative cooling for a direct observation. The fact that we do not see any significant effect of inelastic loss highlights the fact that the extremely large positive and negative scattering lengths attainable with fermionic lithium offer intriguing new possibilities for experiments on interacting Fermi gases.

We thank R. G. Hulet and H. Stoof for very useful discussions and V. Venturi for valuable input. Support by the Austrian Science Fund (FWF) within Project No. P15115 and SFB 15 and by the Institut für Quanteninformation GesmbH is gratefully acknowledged.

Shortly before submission of the present Letter we learned about the measurements of the group of J. E. Thomas on the zero crossing of the scattering length which agree with our data.

[1] S. Inouye *et al.*, Nature (London) **392**, 151 (1998).
[2] P. Courteille *et al.*, Phys. Rev. Lett. **81**, 69 (1998).
[3] V. Vuletić, A. J. Kerman, C. Chin, and S. Chu, Phys. Rev. Lett. **82**, 1406 (1999).
[4] S. Cornish *et al.*, Phys. Rev. Lett. **85**, 1795 (2000).
[5] E. A. Donley, N. R. Claussen, S. T. Thompson, and C. E. Wieman, Nature (London) **417**, 529 (2002).
[6] L. Khaykovich *et al.*, Science **296**, 1290 (2002).
[7] K. Strecker, G. Partridge, A. Truscott, and R. Hulet, Nature (London) **417**, 150 (2002).
[8] H. T. C. Stoof, M. Houbiers, C. Sackett, and R. Hulet, Phys. Rev. Lett. **76**, 10 (1996).
[9] M. Holland, S. Kokkelmans, M. Chiofalo, and R. Walser, Phys. Rev. Lett. **87**, 120406 (2001).
[10] E. Timmermans, K. Furuya, P. W. Milonni, and A. K. Kerman, Phys. Lett. A **285**, 228 (2001).
[11] M. L. Chiofalo, S. J. J. M. F. Kokkelmans, J. L. Milstein, and M. J. Holland, Phys. Rev. Lett. **88**, 090402 (2002).
[12] T. Loftus *et al.*, Phys. Rev. Lett. **88**, 173201 (2002).
[13] M. Houbiers, H. T. C. Stoof, W. McAlexander, and R. Hulet, Phys. Rev. A **57**, R1497 (1998).
[14] S. Kokkelmans *et al.*, Phys. Rev. A **65**, 053617 (2002).
[15] V. Venturi and C. Williams (private communication).
[16] S. Granade, M. Gehm, K. O'Hara, and J. Thomas, Phys. Rev. Lett. **88**, 120405 (2002).
[17] A. Mosk *et al.*, Opt. Lett. **26**, 1837 (2001).
[18] C. Chin, V. Vuletić, A. J. Kerman, and S. Chu, Phys. Rev. Lett. **85**, 2717 (2000).
[19] O. J. Luiten, M. W. Reynolds, and J. T. M. Walraven, Phys. Rev. A **53**, 381 (1996).
[20] A finite collision energy E_C leads to a shift of $+0.7G \times E_C/(k_B \times 100\ \mu\text{K})$ [15], which for our data stays within the error.
[21] K. Dieckmann *et al.*, cond-mat/0207046v2.