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s-wave elastic collisions between cold ground-state ^{87}Rb atoms

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We have measured the elastic-scattering cross section of ^{87}Rb atoms in the $|F=1,m_F=-1\rangle$ ground state at 25 μK. The cross section is almost purely s wave at these temperatures and has a value of $(5.4\pm1.3)\times10^{-12}$ cm^2. We have searched for the predicted Feshbach-type resonances in the elastic cross section [Tiesinga *et al.*, Phys. Rev. A **46**, 1167 (1992)] as a function of magnetic field. There are no resonances with a magnetic-field width $\geqslant 2$ G over a magnetic-field range of 15–540 G.

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Many of the interesting applications of laser-cooled atoms, such as precision measurements, atomic clocks, Bose-Einstein condensation, or spin waves, require a fundamental understanding of very-low-temperature ground-state collisions. The ground-state potentials of the heavier alkali-metal atoms such as Rb and Cs are not sufficiently well known to predict the collisional cross sections. Because of the low collision rates (<1 Hz for densities of 10^{10} cm^{-3}) and low energy transfers (10^{-9} eV), cold ground-state collisions are also difficult to observe experimentally. Recent published measurements are restricted to the elastic cross section for the $|3,-3\rangle$ ground state of ^{133}Cs [2] and the frequency shift of magnetic resonance lines in ^{133}Cs [3]. Here, we present measurements of the s-wave elastic collision cross section for ^{87}Rb atoms in the $|F=1,m_F=-1\rangle$ ground state.

For two colliding spin-polarized atoms in the lower hyperfine ground state Tiesinga *et al.* have predicted Feshbach-type resonances between the incoming atomic states and quasibound molecular states [1]. Since the magnetic moment of the molecular state differs from that of the colliding atoms, the resonances will occur at specific values of the bias magnetic field. The sign of the scattering length changes across a resonance, so that the existence of such a resonance could be very important for the realization of a Bose-Einstein condensate that requires a positive scattering length [4]. For a relative momentum of $\hbar k$, the resonant cross section is $8\pi/k^2$ or about ten times larger than our measured nonresonant cross section at 25 μK. An increased elastic cross section would assist current efforts to achieve runaway evaporative cooling [5] of trapped alkali-metal atoms [6,7]. Unfortunately, given the current accuracy of the Rb interatomic potential, it is impossible to predict the position of the resonances. We have searched for a resonance in the elastic cross section over a magnetic-field range of 15–540 G. We did not find a resonance in the cross section with a width $\geqslant 2$ G up to 540 G.

Our technique is quite similar to the cross-dimensional mixing technique introduced in Ref. [2]. Atoms are magnetically trapped in a harmonic well which has different oscillation frequencies, $\nu_x\neq\nu_y\neq\nu_z$, along each dimension. In this work, we use gravitational Sisyphus cooling [8] to cool the vertical dimension to an effective temperature T_z, much colder than the horizontal temperatures T_x and T_y. Elastic collisions will drive the sample towards thermal equilibrium. Starting from the Boltzmann equation, we can derive the rate of change of the total energy in the vertical direction as [9]

$$\frac{dT_z}{dt}\approx n\sigma\sqrt{\frac{k_BT_h}{m}}T_h\,\frac{\sqrt{\pi}}{4}\left[1-0.6\left(\frac{T_z}{T_h}\right)-0.4\left(\frac{T_z}{T_h}\right)^2\right], \quad (1)$$

where m is the mass of ^{87}Rb, k_B is Boltzmann's constant, $T_h=(T_x+T_y)/2$, and $n=\int n^2(\mathbf{r})d^3r$ for a normalized density distribution $n(\mathbf{r})$. To derive this equation, we assume an angle-independent and energy-independent cross section σ and separable Gaussian distributions of position and velocity in all three dimensions. By cooling the vertical dimension, rather than heating the $\hat{\mathbf{y}}$ dimension as in Ref. [2], we improve the signal-to-noise ratio of the measurement since the initial density n is higher and the initial difference between T_h and T_z is larger. In addition, our average temperature of 25 μK corresponds to a significantly longer de Broglie wavelength than in Ref. [2], implying that the collisions are almost completely s wave in character.

To load the magnetic trap, we initially collect 10^7–10^8 atoms using diode lasers and a standard vapor-cell magneto-optic trap (MOT) [10,11]. The atom sample is cooled further with an optical molasses [12] and then loaded *in situ* into a magnetic trap. The trap is formed by a "baseball" coil, a pair of Helmholtz coils, and a pair of anti-Helmholtz coils that provide a magnetic-field gradient to balance the force of gravity [8,2,13]. Bias magnetic fields in the range of 15 to 540 G can be achieved with our power supplies by varying the current in the baseball and Helmholtz coils. After loading the trap with a bias field of 25 G and oscillation frequencies of $\nu_x=14.0$, $\nu_y=8.8$, and $\nu_z=4.4$ Hz, we cool the vertical dimensions using gravitational Sisyphus cooling [8]. After cooling we change the bias magnetic field in 0.5–1 sec so that the corresponding changes in the trap oscillation frequencies are adiabatic.

The subsequent thermalization rate at the given bias field is determined by observing the increase in the width of the vertical distribution ($\propto T_z^{1/2}$) over time. To determine the spatial distribution, the magnetic trap is suddenly (<1 msec) turned off and the atoms excited with a 1-msec pulse of both the hyperfine repumping light $5s\,^2S_{1/2}(F=1)\rightarrow5p\,^2P_{3/2}(F'=2)$ and laser light tuned three linewidths to the red of the $5s\,^2S_{1/2}(F=2)\rightarrow5p\,^2P_{3/2}(F'=3)$ cycling transition. The resulting fluorescence is imaged with a

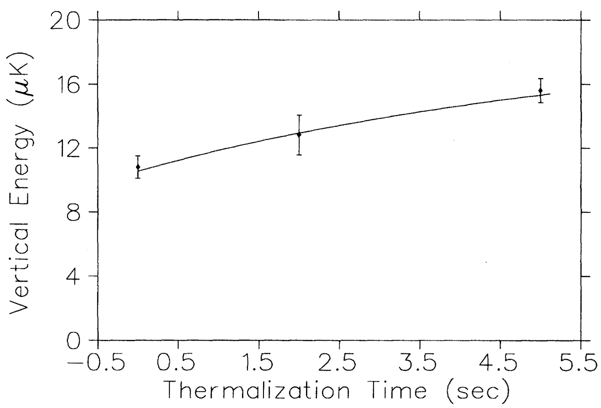

FIG. 1. The vertical energy as a function of time calculated from the variance of the vertical distribution. To avoid systematic errors associated with "breathing" modes of the distribution, each data point is an average of ten points taken at fractions of an oscillation period. In addition, the horizontal spatial profile of the cloud is imaged to determine T_h and n. These particular data represent a single measurement of σ at a bias field of 240 G.

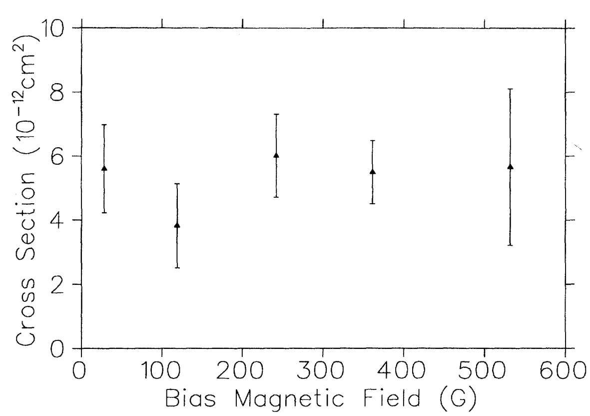

FIG. 2. The elastic cross section as a function of magnetic field. Each point is the average of at least two measurements of the type illustrated in Fig. 1. The error bars shown are relative and do not include any overall errors in normalization.

charge-coupled-device (CCD) camera and one raster of the image digitized and stored. From this image, we calculate the variance of the spatial distribution $\langle x_i^2 \rangle$ and the effective temperature associated with that dimension as $T_i = m\omega_i^2 \langle x_i^2 \rangle / k_B$. In addition, the total number of atoms N is determined by the fluorescence on a photodiode. The lifetime of the trapped atoms is ~ 8 sec. The average density n is time dependent both through the time dependence of N and the change in the spatial profile of the atom cloud as it comes into thermal equilibrium.

The derivation of Eq. (1) assumed a Boltzmann energy distribution for each dimension. In the horizontal dimensions, the cloud shapes are indeed very close to Gaussian and can be characterized by temperatures T_x and T_y which range from 20–40 μK, depending on ν_x and ν_y. After gravitational Sisyphus cooling, the vertical dimension is better approximated as the sum of two Gaussians, with the respective effective temperatures of ~ 1.3 and ~ 11 μK at $\nu_z = 4.4$ Hz. (For different vertical spring constants these temperatures will roughly scale as ν_z.) Typically the narrow Gaussian consists of about 60% of the atoms and the wider Gaussian contains the remaining 40% of the atoms, although the percentages change as the cloud thermalizes. The effective temperature is calculated from the total energy associated with the vertical dimension as $T_z = E_z / k_B$. Since $T_z < T_h/2$ for our data, the correction to the right-hand side of Eq. (1) for the non-Gaussian vertical distribution is negligible [9]. Since T_z increases by at most 5 $\mu\text{K} \ll T_h$, we integrate Eq. (1) including the time dependence of n but holding T_h constant. Figure 1 shows the result of a fit of $T_z(t)$ to the integrated Eq. (1).

In Fig. 2, we present the elastic cross section as a function of bias magnetic field. Averaging the cross section over the magnetic field gives $\sigma = (5.4 \pm 0.8 \pm 1.0) \times 10^{-12}$ cm^2, where the first error is the standard deviation of the data in Fig. 2 and the second error is due to normalization uncertainties in n and T_i. The magnitude of the scattering length is then $|a| = 46 \pm 11$ Å, compared to a thermally averaged relative de Broglie wavelength at 25 μK of $\langle \lambda_{\text{de B}} \rangle \approx 1050$ Å. For comparison, the maximum possible cross section is $\sigma_R = \langle 2\lambda_{\text{de B}}^2 / \pi \rangle = \langle 8\pi / k^2 \rangle \approx 10^{-10}$ cm^2, where $\hbar k$ is the relative momentum of the colliding atoms and the angle brackets denote a thermal average.

There are several possible systematics affecting the cross-section measurements. First, residual anharmonicities in the trap potential can couple different dimensions, imitating the effects of elastic collisions. At the trap frequencies chosen for our measurements, we have determined that this coupling is negligible by comparing the thermalization rate of a low-density and high-density sample. Glancing collisions with hot background atoms can transfer an amount of energy to trapped atoms which is less than the trap depth. These collisions create a distribution of "hot" trapped atoms in addition to the original cold distribution. The fluorescence from this diffuse cloud is below the noise of our CCD images but is included in the total measured fluorescence of the cloud. Since the energy-transfer cross section for glancing collisions is constant across the energy distribution of the sample, there is no distortion of the cloud profile that would imitate thermalization. (In Ref. [2] the atom sample was hotter so that atoms were not removed uniformly from the original distribution, resulting in an apparent heating of the sample and an important systematic.) However, atoms in this second diffuse distribution can transfer energy back to the original cold distribution through elastic collisions. After 6 sec, this hot distribution holds $\sim 15\%$ of the atoms for the deepest trap potentials. At lower trap potentials, the number is considerably smaller. Therefore, by comparing the elastic cross section measured at a constant bias field but different trap depths, we are able to show this effect on σ to be under 20%.

A final possible systematic in our measurements lies in the use of Eq. (1), which assumes an energy and angle-independent cross section. Clearly any non-s-wave contribution to the cross section will have a dependence on both energy and angle. Since the colliding particles are spin-polarized bosons, only even angular momentum partial waves (e.g., s, d, . . .) will contribute to the cross section. From the C_6 coefficient for Rb [14], we can calculate the

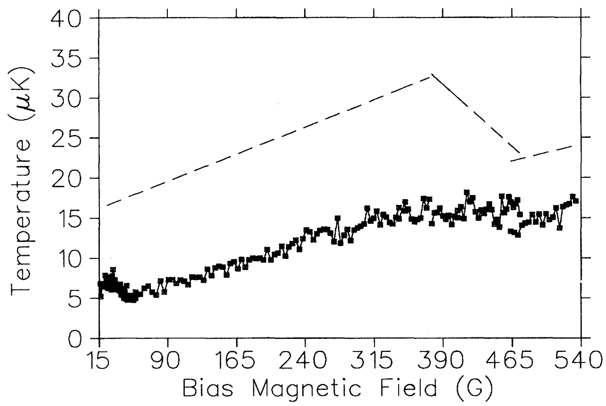

FIG. 3. The effective vertical temperature of the cloud after 4 sec of thermalization time as a function of bias magnetic field. The data points are spaced by ~ 4 G, and each represents an average of 3–5 images of the cloud. For a 10-G-wide Feshbach resonance, the atomic sample would be almost completely thermalized with a vertical temperature given by the dashed line. The various slopes of the dashed line are a result of the complicated dependence of ν_x, ν_y, and ν_z on the baseball and Helmholtz coil magnetic fields.

(nonresonant) d-wave contribution to the elastic cross section to be $\sigma_2 \sim 10^{-4}\sigma$. An accidental d-wave shape resonance would have a fractional energy width $\ll 10\%$ and would be unobservable.

In the absence of a resonance, the s-wave cross section will have an energy dependence to lowest order in k given by $\sigma \approx 8\pi a^2/(1+a^2k^2)$. At 25 μK, $(ak)^2 \approx 0.14$, so that given our experimental accuracy we can assume $\sigma \approx 8\pi a^2$ in deriving Eq. (1). Cross-section measurements taken at a fixed bias magnetic field over a temperature range of 20–60 μK show no temperature dependence to within our signal-to-noise ratio.

Finally, the most interesting possible energy dependence of the cross section would arise from a Feshbach resonance. As discussed below, such a resonance will depend on the bias magnetic field. In order to search for possible resonances in the elastic cross section, we measured the variance of the cloud after it had thermalized for 4 sec. The results as a function of magnetic field are shown in Fig. 3. The trapped atoms sample a spread in magnetic field of $(2\sqrt{\langle z^2 \rangle})31$ G/cm ≈ 3 G, so we incremented the bias field in steps of ~ 4 G. If a resonance occurred at a magnetic-field value between two adjacent data points, a peak would be observed in the figure with a signal-to-noise ratio ≥ 3 for a full width at half maximum of the resonance of 2 G or more.

Feshbach resonances can occur when there is an energy degeneracy and coupling between an incoming unbound state and a quasibound molecular state. Since the magnetic moment of the incoming state is in general very different from that of the molecular state, the existence of such a resonance will depend strongly on the bias magnetic field. Tiesinga *et al.* [1] discuss Feshbach resonances resulting from the competition between the exchange interaction, $V_{ex}(r)\mathbf{S}_1 \cdot \mathbf{S}_2$, and either the Zeeman interaction or the hyperfine interaction, $a_{hf}\mathbf{S}_i \cdot \mathbf{I}_i$, where $\mathbf{S}_i$ ($\mathbf{I}_i$) is the electron (nuclear) spin of a single atom. Based on Ref. [1], we expect the width of Feshbach resonances associated with the Zeeman interaction to be narrower than 1 G for our low magnetic fields. However, Tiesinga *et al.* report a broad Feshbach resonance in ^{133}Cs associated with the hyperfine interaction with a width of ~ 10 G. By scanning the magnetic field, we hoped to observe the analogous resonance in a gas of ^{87}Rb.

Despite the uncertainties in the ^{87}Rb interatomic potential, it is useful to estimate the magnetic-field spacing of such resonances at low fields. Normally the exchange interaction greatly exceeds the hyperfine interaction over the classically accessible region of a molecular bound state. In contrast, high-lying quasibound molecular states extend far into the region where the hyperfine coupling is greater than the exchange interaction. As a result it is difficult to assign spin quantum numbers to these states. Nevertheless, we can consider a Feshbach resonance between our incoming state and a state associated with the potential that dissociates to two $|2,-1\rangle$ atoms. Such a state will have a magnetic moment of $\sim +\mu_B$, which will be adjusted by the effects of the exchange interaction at small r. At zero magnetic field the incoming state $|1,-1\rangle \otimes |1,-1\rangle$ has a magnetic moment of $-\mu_B$ and an energy of $-4a_{hf}+E$ with respect to two dissociating $|2,-1\rangle$ atoms. Increasing the magnetic field raises the energy of the incoming state and lowers the potential curve associated with the quasibound state. Given the C_6 coefficient, the maximum energy separation between the incoming state and the nearest quasibound state is 7.9 GHz at zero magnetic field [15]. For a difference in the magnetic moments of the two states of $2\mu_B$, we would therefore expect a resonance within a bias field of 0–2.8 kG. A similar rough analysis suggests that a resonance with a second quasibound state that dissociates to an outgoing state $|1,-1\rangle \otimes |2,-1\rangle$ is also possible within a bias field of 0–3.3 kG. Therefore, there is a probability of 1/3 that there is a resonance within 540 G of zero field. (An identical analysis in the standard singlet-triplet molecular basis also gives a probability of one-third for a resonance within 540 G.) Current efforts at understanding the Rb-Rb interatomic potential [16] may lead to a narrow predicted range of the resonance position.

The lack of a resonance in the 15–540 G range, while not as informative as the observation of a resonance, does put some constraints on the interatomic potential. Unfortunately, because of the limited power dissipation in our magnet coils, we cannot currently search for a resonance at fields much higher than 540 G. One possible method to circumvent the experimental difficulties of sweeping a field from 0 to 3 kG is to couple the incoming state with a quasibound molecular state by applying resonant microwave radiation. Depending on the strength of the microwave radiation required, it may be experimentally easier to scan the microwave frequency several GHz than to scan the bias magnetic field over this range.

Our measurement should assist the optimization of evaporative cooling of Rb in the new tightly confining magnetic trap recently demonstrated by Petrich, Anderson, Ensher, and Cornell [6]. In Ref. [8], we presented gravitational Sisyphus cooling as a new method for cooling magnetically trapped atoms. Our value of the elastic collision cross section implies that gravitational Sisyphus cooling, coupled with an improved experimental apparatus to increase the trap lifetime and number of atoms, should increase the thermalization rate to a value where "runaway" evaporative cooling can proceed.

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