Isotopic difference in the heteronuclear loss rate in a two-species surface trap

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We have realized a two-species mirror-magneto-optical trap containing a mixture of ^{87}Rb (^{85}Rb) and ^{133}Cs atoms. Using this trap, we have measured the heteronuclear collisional loss rate $\beta'_{\text{Rb-Cs}}$ due to intraspecies cold collisions. We find a distinct difference in the magnitude and intensity dependence of $\beta'_{\text{Rb-Cs}}$ for the two isotopes ^{87}Rb and ^{85}Rb which we attribute to the different ground-state hyperfine splitting energies of the two isotopes.

Since the first experiments in 1999 [1] demonstrating the trapping of atoms using micron scale wires fabricated on a reflective substrate (the so-called "atom chip") there has been increased interest in techniques for cooling, trapping, and controlling atoms at surfaces. Various devices have been proposed and are now being realized in the laboratory including atomic beamsplitters and wave guides [2–5]. Indeed, sufficient progress has been made that a Bose-Einstein condensate (BEC) can now be created and manipulated using atom-chip techniques [6,7]. In a parallel development, the investigation of cold atomic clouds of mixed atomic species has also attracted substantial attention, giving rise to intense efforts to generate cold heteronuclear molecules [8,9] for application to fundamental measurements [4] and for quantum information technologies [9]. To date, however, there have been no reports of mixed species trapping with surface trap technologies.

In this paper we report the realization of a two-species surface trap — the two-species mirror-magneto-optical trap (TSMMOT). As with other atom traps, the performance of the trap (e.g., density, number, etc.) is strongly affected by collisionally induced trap loss [10–12]. We have therefore used the TSMMOT to investigate the cold collisions of atomic Cs with ^{87}Rb (^{85}Rb). We focus on measurements made in the low intensity regime ($2I_{\text{sat}} \lesssim I \lesssim 8I_{\text{sat}}$, where I_{sat} is the atomic trapping transition saturation intensity). Mixed species Cs-Rb trap losses have been recently characterized in a standard MOT over a broad range of laser intensities [12]. Our results are distinct in that we find an isotopic difference, which to our knowledge has not been previously observed, and which we attribute to ground-state interspecies hyperfine changing processes.

In our experiments, trapping light was provided by line-narrowed extended cavity diode lasers locked to the trapping transitions using a dichroic scheme [13,14]. Acousto-optical modulators were used to detune the light from the locking point to the cooling transition by $-1\,\Gamma_{\text{Rb}}(-2.1\,\Gamma_{\text{Rb}})$ for ^{85}Rb(^{87}Rb) and by $-1.3\,\Gamma_{\text{Cs}}$ for Cs. To assure uniform Gaussian beams, all trapping light was passed through single-mode optical fibers. After the fibers, the beams had an $1/e^2$ waist of 0.4 cm. A series of polarizing beam splitter cubes and half-wave plates were used to mix the trapping light and to tune the individual intensities of the repumping

and trapping light of each species. The adjustments were made to optimize the size, shape, and overlap of both atomic clouds.

The surface used for this TSMMOT configuration was fabricated in-house using thin-film hybrid technology [1]: a top layer 0.7 μm thick of highly reflective (95%) Ag was evaporated onto a 1 μm SiO$_2$ sputtered layer, all deposited onto a 300-μm-thick Si wafer. Similar techniques were used to pattern chips capable of magnetic surface trapping. The typical TSMMOT hovered $\sim$3.5 mm above the mirror surface to ensure that surface effects play no role. Taking the geometry into account [15], the maximum total intensity within the TSMMOT region is 13 mW/cm^2 for Rb and 53 mW/cm^2 for Cs. A set of anti-Helmholtz coils produced a magnetic field gradient of up to 40 G/cm (typically we used 30 G/cm). The specific value of the field gradient did not qualitatively affect our results. Three orthogonal Helmholtz pairs ("trim coils") were used to compensate for residual stray magnetic fields. In combination with small displacements of the trapping laser beams, the trim coils assisted in optimizing the overlap between the two atomic species. The pressure in the chamber was maintained at $\sim$10^{-8} Torr. The atoms were introduced using getter sources placed inside the vacuum chamber approximately 5 cm from the B-field minimum [16].

To assure full three-dimensional overlap of the two trapped species, the clouds were imaged with a pair of charge-coupled device (CCD) cameras aligned on separate axes perpendicular to the chip. A third high-performance CCD (high linearity) was used to image the MOTs and measure their spatial distributions. The shape of the two clouds was that of an oblate spheroid. The measured waists are noted in Table I. The number of trapped atoms was determined by measuring the fluorescence using two calibrated photodetectors combined with narrow-band interference filters (bandwidth of about 9 nm) capable of isolating the fluorescence of the individual atomic species. The fluorescence measurement was converted to an absolute atom number by taking into account the trap-laser intensities at the position of the trap [15], the detunings, polarizations, and spatial profiles of the lasers, and by using a weighted and averaged Clebsch-Gordon coefficient to determine the atomic saturation intensity. The total number of trapped atoms was typically 2

TABLE I. Experimental parameters used to characterize ^{85}Rb and ^{87}Rb with Cs.

Parameter	^{85}Rb	^{133}Cs	^{87}Rb
Cooling transition	$5S_{1/2}(F=3)$ $\rightarrow 5P_{3/2}(F'=4)$	$6S_{1/2}(F=4)$ $\rightarrow 6P_{3/2}(F'=5)$	$5S_{1/2}(F=2)$ $\rightarrow 5P_{3/2}(F'=3)$
Natural linewidth Γ(MHz)	$2\pi \times 5.98$	$2\pi \times 5.22$	$2\pi \times 6.07$
Saturation intensity I_{sat}(mW/cm^2)	1.64	1.10	1.67
Detuning from cooling transition	$-1.0\,\Gamma_{Rb}$	$-1.3\,\Gamma_{Cs}$	$-2.1\,\Gamma_{Rb}$
Total intensity I_{tot}(mW/cm^2)	4–13	53	4–13
Atom number N	1×10^7–2×10^7	1×10^7	3×10^6–9×10^6
Vertical waist with (without) Cs(μm)	215–300(260–330)	447	250–395(340–845)
Horizontal waist with (without) Cs(μm)	420–470(420–570)	169	115–150(130–170)
Peak density n with (without) Cs(cm^{-3})	$2\times10^{11}(3$–$4.5\times10^{11})$	1.5×10^{11}	$6\times10^{10}(4\times10^{10}$–$1\times10^{11})$

$\times10^7(9\times10^6)$ for ^{85}Rb(^{87}Rb) and 1×10^7 for Cs. This along with our waist measurements yields peak densities of $4.5\times10^{11}(1\times10^{11})$ atoms/cm^3 for ^{85}Rb(^{87}Rb) and 1.5×10^{11} atoms/cm^3 for Cs.

The amount of collision induced traploss depended critically on the overlap between the two atomic clouds. During all experiments, the overlap was $\gtrsim95\%$ by volume.

The Cs MOT was imposed onto the Rb MOT by controlled blocking and unblocking of the repump light for Cs. Figure 1 shows the loading behavior of the Rb atoms in the absence and presence of Cs. Losses as large as 78% in the Rb atom number due to Cs were observed. By fitting this data to a transient loading rate equation [10,12], the heteronuclear loss rate was obtained. The dependence of trap loss on the total intensity of the Rb trap laser was measured by keeping all parameters of the Cs trap (intensity, detuning, number of Cs atoms in the trap) constant.

The collisions of atoms in a MOT can be characterized by the interplay of the loading and loss rate of trapped atoms. The time-dependent rate equations that model this process can be written

$$d_t N_{Rb}(t) = \tau_{Rb} - \gamma_{Rb}N_{Rb}(t) - \beta'_{Rb\text{-}Cs}n_{Cs}N_{Rb}(t) - \beta_{Rb\text{-}Rb}n_{Rb}N_{Rb}(t), \quad (1)$$

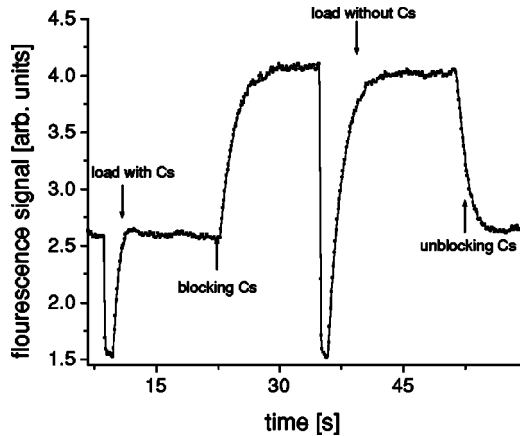where N_{Rb} is the number of Rb atoms, τ_{Rb} is the trap filling

FIG. 1. The transient loading signal of ^{87}Rb, both with and without Cs, as a function of time.

rate, γ_{Rb} is the loss coefficient due to background collisions, $\beta_{Rb\text{-}Rb}$ is the loss rate due to homonuclear collisions of atoms of one species, and $\beta'_{Rb\text{-}Cs}$ is the loss rate due to heteronuclear collisions of atoms between the two species. The atom number densities, n_{Cs} and n_{Rb}, are experimentally defined as the peak number of atoms divided by the total volume, calculated using the Gaussian $1/e^2$ waists. Similar to previous treatments in the literature, we find that for our trapped atom number and density, we are in the density-limited regime [12].

In our experiments, we observe that the trapped atom number and density for the Cs trap is essentially undisturbed by the introduction of Rb atoms into the trap, as also seen in Ref. [12]. Hence in our analysis we treat the Cs density as a constant. By contrast, the number of trapped Rb atoms is dramatically affected by the presence of Cs atoms in the trap.

We begin our analysis by noting that $\beta'_{Rb\text{-}Cs} \gg \beta_{Rb\text{-}Rb}$ [12,17,18]. Equation (1) can then be written as

$$d_t N_{Rb}(t) = \tau_{Rb} - (\gamma_{Rb} + \beta'_{Rb\text{-}Cs}n_{Cs})N_{Rb}(t) = \tau_{Rb} - \gamma'_{Rb}N_{Rb}(t), \quad (2)$$

where γ'_{Rb} is the total loss rate of the mixed trap. For the parameters of our experiment (chamber pressure, etc.), even in the absence of Cs, $\beta_{Rb\text{-}Rb}$ can be neglected and Eq. (1) becomes

$$d_t N_{Rb}(t) = \tau_{Rb} - \gamma'_{Rb}N_{Rb}(t). \quad (3)$$

Combining Eqs. (2) and (3), $\beta'_{Rb\text{-}Cs}$ is given by

$$\beta'_{Rb\text{-}Cs} = \frac{(\gamma'_{Rb} - \gamma_{Rb})}{n_{Cs}}. \quad (4)$$

Figure 2(a) shows the measured average losses of Rb due to Cs. The error bars correspond to standard deviations in mean value, averaged over repeated experiments performed while keeping experimental parameters constant. The losses decrease almost linearly with increasing Rb laser intensity. They also show a distinct isotopic difference: the losses for ^{87}Rb are greater than those for ^{85}Rb. This behavior is also seen in the total loss rate which is shown in Fig. 2(b) where we plot the total loss rate γ_{Rb} (for pure Rb) and the total loss rate γ'_{Rb} (for Rb+Cs) on the same graph. We observe no
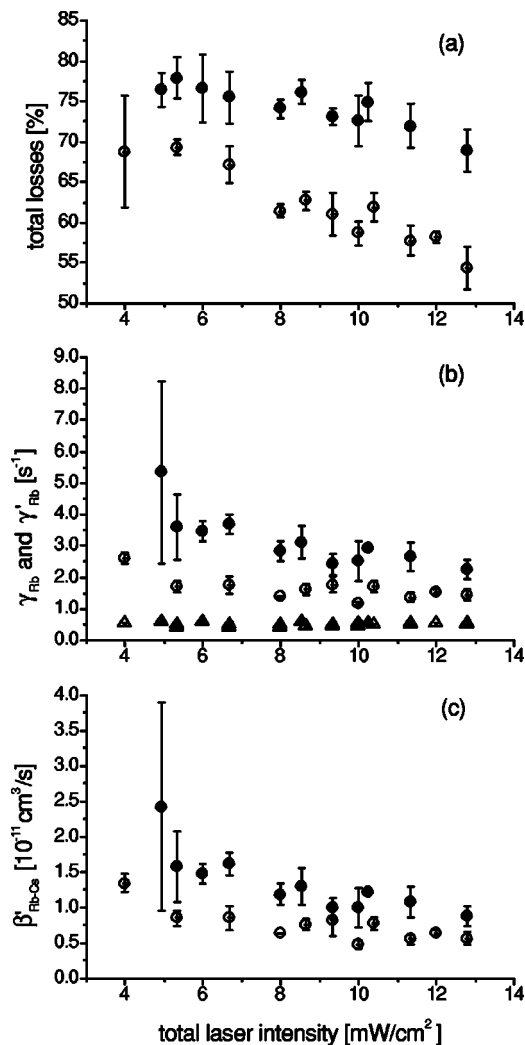
FIG. 2. Trap losses for both isotopes as a function of Rb laser intensity. The solid and hollow symbols in all plots represent ^{87}Rb and ^{85}Rb, respectively. Plot (a) shows the overall losses in percent, plot (b) the total loss rates γ'_{Rb} (circles) and γ_{Rb} (triangles), with and without Cs, and plot (c) β'_{Rb-Cs}.

change in γ_{Rb} (pure Rb trap) for this intensity regime and see no isotopic difference. This is consistent with previous work [17,19]. However, the total loss rate γ'_{Rb} changed dramatically in the presence of Cs. Again, the averaged loss rate for ^{87}Rb is consistently higher than for ^{85}Rb. This isotopic difference is transferred onto β'_{Rb-Cs} [Fig. 2(c)] which was calculated using Eq. (4).

We note that the absolute values of β'_{Rb-Cs} have significant uncertainties which arise from systematics in determining the exact atom number (not included in our error bars). However, this uncertainty does not change the observed isotopic difference.

We believe that the the isotopic difference is due to the difference in the hyperfine ground-state splitting energy of the two isotopes of Rb [17,19]. Experimentally, isotopic difference in trap loss due to ground state hyperfine structure were first observed in experiments performed using pure Rb traps [17]. Phenomenologically, the effect was explained by noting that the trap depth, which decreases with decreasing

intensity, is approximately the same for the two isotopes whereas the ground-state hyperfine splitting energy is smaller for ^{85}Rb(3.04 GHz) than for ^{87}Rb (6.83 GHz). As hyperfine changing collisions involving at least one ground-state ^{87}Rb release more energy than those involving ^{85}Rb they cause more trap loss in the low intensity regime. In particular, as a function of the trap laser intensity, β_{Rb-Rb} has been observed to decrease with increasing intensity, reach a minimum and increase again for higher intensities. For an ideally aligned MOT, the minimum is reached when the trap depth equals the hyperfine splitting energy [17]. As the hyperfine energies for the two Rb isotopes are different, this minimum occurs at different trap intensities. For a slightly misaligned MOT this minimum is shifted to higher intensities, but the shape of the curves and the isotopic difference is preserved.

We find that the behavior of β'_{Rb-Cs} parallels the homonuclear Rb experiments. In the low intensity regime, we see a decrease of β'_{Rb-Cs} with increasing intensity [10,12]. In addition, the slope of the curve is found to be smaller for ^{85}Rb than for ^{87}Rb, as the hyperfine splitting energy of ^{85}Rb is smaller and therefore the minimum is reached at lower intensities.

It is well known that trap-loss measurements integrate a variety of collisional loss processes, and our measurements share this feature. Therefore, other collision processes are likely contributing to the value of β'_{Rb-Cs} and so we briefly review the dominant possibilities and their potential effect on our conclusion. Because the laser intensity for Rb is fairly low, we have assumed in our discussion that most of the Rb atoms are in the ground state. However, given the high Cs trap-light intensity, a larger fraction of the Cs atoms are in the excited state. As a result, both Cs fine structure and Cs hyperfine structure changing collisions between a ground state Rb and an excited state Cs are possible. Since the Cs parameters are kept constant, these processes will only add a constant (Rb laser-intensity independent) offset to the observed values of β'_{Rb-Cs}, thus shifting both curves in the same way. Hence, the observed isotopic difference will be preserved independent of whether a Cs collision partner is in the ground or excited state. Furthermore, changes of the excited-atom hyperfine state will not make a significant contribution to trap loss because the excited-state hyperfine splittings are much smaller than the ground-state splittings. Last, we note that we have not included either radiative escape or Rb fine structure changing collisions. For excited Cs, this again can be justified by noting that the associated loss will be independent of Rb trap-laser intensity. For the case of a (weak) excited state population of Rb atoms, we point out that each of these loss processes should contribute losses that increase with increasing Rb laser intensity, whereas all of the observed rates decrease over the range of laser intensities studied.

Finally, we note that ground-state heteronuclear hyperfine changing collisions have also been observed in mixtures of sodium and rubidium in our labs [11], however, that work was not performed in the environment of a surface trap.

In summary we presented heteronuclear trap loss measurements in a mixed Rb-Cs TSMMOT. At low intensites,

there is an isotopic difference between ^{85}Rb and ^{87}Rb. Our loss measurements agree well with previous data obtained for a mixed Rb-Cs trap, however no isotopic difference was reported in that work. With well overlapped cloud centers, losses up to 78% can be obtained. To our knowledge, this is the highest loss reported for a mixed Rb-Cs MOT. The two-species mirror MOT can be used as a robust atom source for loading a double species atom chip [2–5], and of creating ultracold heteronuclear molecules close to the surface [8]. Both experiments would open up ways in quantum informa-tion processing. In this regime, surface effects could play a key role in total losses mainly arising from decoherent effects.

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