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 $\beta_{Rb-Cs}$ due to intra-species cold collisions. We find a distinct difference in the magnitude and intensity dependence of $\beta_{Rb-Cs}$ for the two isotopes $^{87}$Rb and $^{85}$Rb which we attribute to the different ground-state hyperfine splitting energies of the two isotopes.

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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 beam splitters and wave guides [2, 3, 4, 5]. Indeed, sufficient progress has been made that a BEC can now be created and manipulated using atom-chip techniques. 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 collisions and for quantum information technologies [7]. 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 [6, 7, 8]. We have therefore used the TSMMOT to investigate the cold collisions of atomic Cs with $^{85}$Rb ($^{87}$Rb). We focus on measurements made in the low intensity regime ($2I_{sat} \leq I \leq 8I_{sat}$ 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 [10].

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 inter-species 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 (DAVLL) scheme [11, 12]. Acousto-optical modulators (AOM) were used to detune the light from the locking point to the cooling transition by -1 $\Gamma_{Rb}$ (-2.1 $\Gamma_{Rb}$) for $^{85}$Rb ($^{87}$Rb) and by -1.3 $\Gamma_{Cs}$ 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 (PBSC) 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 $\mu$m thick of highly reflective (95%) Ag was evaporated onto a 1 $\mu$m SiO$_2$ sputtered layer, all deposited onto a 300 $\mu$m thick Si wafer. Similar techniques were used to pattern chips capable of magnetic surface trapping. The typical TSMMOT hovered ~3.5 mm above the mirror-surface to ensure that surface effects play no role. Taking the geometry into account [13], 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 typically produced a magnetic field gradient of about 40 G/cm. Three orthogonal Helmholtz pairs (“trim coils”), were used to compensate for residual stray magnetic fields and to guarantee good overlap between the two atomic species. The pressure in the chamber was maintained at $\leq 10^{-8}$ Torr. The atoms were introduced using getter sources placed inside the vacuum chamber approximately 5 cm from the B-field minimum [14].

To assure full three-dimensional overlap of the two trapped species, the clouds were imaged with a pair of 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 total number of trapped atoms was typically $2 \times 10^7$ $(9 \times 10^6)$ for $^{87}$Rb ($^{85}$Rb) and $1 \times 10^7$ for Cs. This along with our waist measurements yields peak densities of $4.5 \times 10^{11}$ $(10^{11})$ atoms/cm$^3$ for Rb and $1.5 \times 10^{11}$ atoms/cm$^3$ for Cs.

The amount of collision induced trap-loss depended critically on the overlap between the two atomic clouds. During all experiments, the overlap was $\gtrsim 95\%$ by volume.
TABLE I: Experimental parameters used to characterize $^{85}$Rb and $^{87}$Rb with Cs.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$^{85}$Rb</th>
<th>$^{133}$Cs</th>
<th>$^{87}$Rb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling transition</td>
<td>$5S_{1/2}(F = 3)$</td>
<td>$6S_{1/2}(F = 4)$</td>
<td>$5S_{1/2}(F = 2)$</td>
</tr>
<tr>
<td>Natural linewidth $\Gamma$ [MHz]</td>
<td>$2\pi \times 5.98$</td>
<td>$2\pi \times 5.22$</td>
<td>$2\pi \times 6.07$</td>
</tr>
<tr>
<td>Saturation intensity $I_{sat}$ [mW/cm$^2$]</td>
<td>1.64</td>
<td>1.10</td>
<td>1.67</td>
</tr>
<tr>
<td>Detuning from cooling transition</td>
<td>$-1.0 \Gamma_{Rb}$</td>
<td>$-1.3 \Gamma_{Cs}$</td>
<td>$-2.1 \Gamma_{Rb}$</td>
</tr>
<tr>
<td>Total intensity $I_{tot}$ [mW/cm$^2$]</td>
<td>4 - 13</td>
<td>53</td>
<td>4 - 13</td>
</tr>
<tr>
<td>Atom number $N$</td>
<td>$1 \times 10^7$ - $2 \times 10^7$</td>
<td>$1 \times 10^7$</td>
<td>$3 \times 10^6$ - $9 \times 10^6$</td>
</tr>
<tr>
<td>horizontal waist with (without) Cs [µm]</td>
<td>420 - 470 (420 - 570)</td>
<td>169</td>
<td>115 - 150 (130 - 170)</td>
</tr>
<tr>
<td>peak density $n$ with (without) Cs [cm$^{-3}$]</td>
<td>$2 \times 10^{11}$ (3 - $4.5 \times 10^{11}$)</td>
<td>$1.5 \times 10^{11}$</td>
<td>$6 \times 10^{10}$ ($4 \times 10^{10}$ - $1 \times 10^{11}$)</td>
</tr>
</tbody>
</table>

The Cs MOT was imposed onto the Rb MOT by controlled blocking and unblocking of the repump light for Cs. Fig. 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 [8, 10], the heteronuclear loss rate was obtained. The dependence of trap loss on the total intensity of the Rb trap laser was measured by keeping the Cs laser intensity and the 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:

$$d_t N_{Rb}(t) = \tau_{Rb} - \gamma_{Rb} N_{Rb}(t) - \beta_{Rb-Cs} n_{Cs} N_{Rb}(t) - \beta_{Rb-Rb} n_{Rb} N_{Rb}(t)$$

where $N_{Rb}$ is the number of Rb atoms, $\tau_{Rb}$ is the trap filling rate, $\gamma_{Rb}$ is the loss coefficient due to background collisions, $\beta_{Rb-Rb}$ is the loss rate due to homonuclear collisions of atoms of one species, and $\beta_{Rb-Cs}$ 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 $1/e^2$ waist. Similar to previous treatments in the literature, we assume that we are in the density-limited regime [10].

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. 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 assuming that $\beta_{Rb-Cs} \gg \beta_{Rb-Rb}$ [10, 13]. Eq. 1 can then be written as

$$d_t N_{Rb}(t) = \tau_{Rb} - (\gamma_{Rb} + \beta_{Rb-Cs} n_{Cs}) N_{Rb}(t)$$

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

$$d_t N_{Rb}(t) = \tau_{Rb} - \gamma_{Rb} N_{Rb}(t)$$

Combining Eqs. 2 and 3 $\beta_{Rb-Cs}$ is given by

$$\beta_{Rb-Cs} = \frac{(\gamma_{Rb} - \gamma_{Rb})}{n_{Cs}}$$

Fig. 2a 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 $^{85}$Rb are greater than those for $^{87}$Rb.
We note that the absolute values of $\beta_{Rb-Cs}$ have significant uncertainties ($\sim 50\%$) which arise from systematics in determining the exact atom number (not included in our error bars). However, this uncertainty is identical for each isotope of Rb and hence does not change the observed isotopic difference.

We attribute the isotopic difference to the difference in the hyperfine ground-state splitting energy of the two isotopes of Rb [15,16]. Experimentally, isotopic difference in trap loss due to ground state hyperfine structure were first observed in experiments performed using pure Rb traps [15]. 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 than for $^{87}$Rb. As hyperfine changing collisions involving $^{87}$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, $\beta_{Rb-Rb}$ 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. 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 $\beta_{Rb-Cs}$ parallels the homonuclear Rb experiments. In the low intensity regime, we see a decrease of $\beta_{Rb-Cs}$ with increasing intensity [8,10]. 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.

We note that ground-state heteronuclear hyperfine changing collisions have also been observed in mixtures of sodium and rubidium in our labs [9] 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 intensities, 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 differences were 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.

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This behavior is also seen in the total loss rate which is shown in Fig. 2, where we plot the total loss rate $\gamma_{Rb}$ (for pure Rb) and the total loss rate $\gamma_{Rb}$ (for Rb+Cs) on the same graph. We observe no change in $\gamma_{Rb}$ (pure Rb trap) for this intensity regime and see no isotopic difference. This is consistent with previous work [12,16]. However, the total loss rate $\gamma_{Rb}$ 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 $\beta_{Rb-Cs}$ (Fig. 2) which was calculated using Eq. [4].

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 $\gamma'Rb$ (circles) and $\gamma_{Rb}$ (triangles), with and without Cs, and plot (c) $\beta_{Rb-Cs}$.
and the Army Research Office.

[13] In our calculation of the excited state occupation, the total beam power was computed with a total of six beams within the MMOT region. Also, the trap offset from the center of the 1/e² beam waist was carefully included.