Measurement of Cs-Cs Elastic Scattering at $T = 30\ \mu$K

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We have measured the elastic collision cross section for spin polarized atomic cesium. Neutral cesium atoms are optically cooled, then loaded into a dc magnetic trap. We infer the scattering rate from the rate at which anisotropies in the initial energy distribution are observed to relax. The cross section for $F=3$, $m_F=-3$ on $F=3$, $m_F=-3$ is $1.5(4)\times10^{-12}$ cm^2, and is independent of temperature from 30 to 250 μK. This determination clarifies the technical requirements for attaining Bose-Einstein condensation in a magnetically trapped Cs vapor. We also study heating due to glancing collisions with 300 K background Cs atoms.

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Recent advances in optical trapping and cooling techniques have allowed collision studies in an entirely new regime of temperatures. In this regime of mK or even colder temperatures, collisions take on unusual characteristics, and often have cross sections many orders of magnitude different from that observed at previously attainable temperatures. Studies of ultralow-temperature collisions have investigated several inelastic processes which cause loss from optical traps: two-photon quasimolecular photoionization [1], photon-assisted collisions [2,3], and hyperfine-state changing collisions [2,4]. All of these processes are inelastic, and while they involve low initial energies for the atoms involved, the final states have kinetic energies of 1 K or greater. It appears that this allows these processes to be treated semiclassically, although the exact accuracy of such treatments is currently a topic of debate. In the work presented here, we examine elastic collisions in which the initial and final energies are both much less than 1 mK. In order to study such low-energy collisions we have developed techniques for observing collisions in very cold samples of magnetically trapped atoms. From these measurements, we deduce the s-wave collision cross section.

The elastic scattering cross section is of particular interest because of its importance in determining the experimental feasibility of achieving Bose-Einstein condensation (BEC) in a cesium vapor. As demonstrated in experiments with spin polarized hydrogen [5], evaporative cooling of magnetically trapped atoms is a promising strategy for achieving the temperature and density necessary for the BEC phase transition, because evaporative cooling does not have the density and temperature limitations encountered in optical cooling and trapping [2,6].

To study the very low energy elastic collisions, we first accumulate Cs atoms in a Zeeman-shift optical trap (ZOT) in a low pressure cell [7]. The atoms are then optically cooled and spin polarized in the $F=3$, $m_F=-3$ state in preparation for magnetic trapping. After all laser light is shut off, magnetic fields are turned on around the atoms *in situ* [7], thereby trapping them.

In this work we use a type of dc magnetic trap which has been previously proposed but, to our knowledge, never used to trap neutral atoms. The field coils consist of wire wound like the seams of a baseball [8]. The 2.5-cm radius "baseball" coil consists of nine turns of No. 3 Cu capillary tubing, and is cooled by flowing water through the tubing. The field at the center of the trap is aligned with gravity. To counteract the force of gravity, a vertical magnetic field gradient of -31 G/cm is generated with an additional pair of circular coils which sit above and below the baseball coils. The superposition of the gravity-canceling fields and the baseball coil fields breaks the cylindrical symmetry of the baseball potential. Although the coil geometry is novel, the fields produced near the center of the trap are the same as for the Ioffe coil configuration; see Refs. [7] and [8]. The baseball coil geometry has a number of desirable characteristics. It has a nonzero minimum in the magnetic field, allows excellent optical access, and provides strong curvatures for a given electrical power. The trap depth and oscillation frequencies of the atoms in the harmonic magnetic trapping potential are related to the current applied through the coil. With 30 A through the coil, the trap has a central field of 50 G with oscillation frequencies of $(\nu_x,\nu_y,\nu_z)=(4,8,4)$ Hz for atoms in the $F=3$, $m_F=-3$ trapped state. At 300 A, the central field is 500 G with oscillation frequencies of (19,20,11) Hz.

When the atoms are first loaded into the magnetic trap from the optical trap the fields are set to give oscillation frequencies $(\nu_x,\nu_y,\nu_z)=(10.5,12.5,6.5)$ Hz. The temperature and density of the magnetically trapped cloud can then be increased by ramping up the strength of the trap around the atoms. We typically load 10^8 atoms with an initial average density of 7×10^9/cm^3 and initial temperature of 30 μK. The temperature is higher than typical optical cooling temperatures due to heating from optical pumping and the addition of magnetic potential energy when the trap is suddenly turned on. As the atoms are compressed in the magnetic trap, the density and temperature can be continuously increased up to 10^{10}/cm^3 and 80 μK, respectively. The lifetime of the atoms in the magnetic trap is limited by collisions with room-tem-

perature background gas. The $1/e$ decay time depends on the pressure and composition of the residual gas, and is typically about 15 s. We have also determined that the trap lifetime is independent of density to within our uncertainty, which indicates that the spin-flip relaxation rate is less than 5×10^{-14} cm^3/s.

For the higher temperature measurements, the atoms are transferred to a separate chamber [9] where they are magnetically trapped. In the double chamber setup, heating in the transfer process kept attainable temperatures over 100 μK.

While the atoms are in the magnetic trap, they do not interact with laser beams and therefore are invisible. To observe the trapped atoms, we abruptly turn off all magnetic fields and illuminate the atoms with a 0.5-ms pulse of resonant laser light. The resulting fluorescence from the atoms is imaged onto a video camera and a photodiode, revealing both the spatial distribution and total number of atoms. Because the measurement is destructive—the photon pressure in the probe beam blasts away the atoms—time evolution of the trapped atoms is studied by repeating the measurement and changing the amount of time the atoms spend in the magnetic trap before the illumination pulse. Shot-to-shot reproducibility is fairly good—measured size, for instance, reproduces to a few percent.

There is always some initial expansion-contraction oscillations and center-of-mass sloshing of the cloud, but these decay away in about 2 s (about twenty oscillations) due to small anharmonicities in the trapping potential. The distribution of atoms in the cloud can be characterized by three temperatures [10], T_x, T_y, and T_z, where T_i is defined in terms of the spring constant k_i and the mean-square extent of the cloud in each direction $k_B T_i \equiv 0.5 k_i \langle r_i^2 \rangle$. Because of asymmetries in the loading process, the three temperatures are initially unequal. Perhaps because the oscillation frequencies in the three different directions are well separated, residual anharmonic terms in the trapping potential are not observed to cause the three temperatures to equilibrate, at least not on the time scale of our experiments. Time evolution of the three temperatures is almost purely due to collisional processes.

The time dependence of the individual one-dimensional cloud sizes (Fig. 1) shows two main effects. The first, visible only at high densities of trapped atoms, is that the sizes tend to be mixed. This is due to the effect we are trying to study, low-temperature elastic collisions between trapped cesium atoms bringing the sample into thermal equilibrium. The observed cross-dimensional equilibration rate can, with further analysis, be turned into an elastic collision cross section. Unfortunately, there is a second effect, visible in both high and low density clouds—the sizes in all three directions tend to increase uniformly because of elastic collisions occurring between trapped atoms and atoms in the 300-K residual vapor in our vacuum chamber. Usually, such a collision imparts a substantial amount of energy to the trapped atom, ejecting it cleanly from the trap with no effect on the remaining trapped atoms. But on occasion (in the event of a glancing angle collision), the background atom imparts such a small amount of energy to the trapped atom that the latter remains in the trap, although with increased energy.

The glancing collisions with background atoms make our study more difficult, but are of some interest in their own right [11]. The collisional energies are very high and hundreds of partial waves are involved, yet a classical treatment of the collisions yields incorrect results. In the extreme glancing collision regime, the momentum transferred can be so small that the associated de Broglie wavelength can be large compared to the classical impact parameter, meaning that diffraction effects become significant. Both trap loss and heating rates vary proportionally with cesium pressure in the background gas, except that, at very low Cs pressures, the heating rate goes nearly to zero while the loss rate approaches ≈ 0.06 s^{-1}. We attribute this residual loss rate with very little accompanying heating to residual amounts of helium gas in the system. Because helium is much lighter than cesium, the diffractive regime begins at a much higher energy transfer, and thus the probability of a He-Cs collision transferring a small enough amount of energy to heat but not to eject an atom is very small [12]. In any case, the heating is evidently isotropic and during data analysis can be separated from the interdimensional equilibration arising from intratrap collisions.

To increase the initial temperature anisotropy, and thus to bring out the observable signature of temperature equalizing collisions, we heat one of the dimensions of the trapped atom distribution using a parametric drive. The trapping field is modulated at twice the y-dimension harmonic frequency. The width of the parametric excitation resonance is about 1 Hz, so this parametric drive does not heat the other two dimensions. After the drive has been turned off, we wait for an interval of time t, and then illuminate the sample and measure the distribution of atoms in the cloud. To simplify the data analysis and interpretation, only very small times t are considered, such that $\Gamma_{\rm mix} t \ll 1$. $\Gamma_{\rm mix}$ is the rate of interdimensional mixing, $\Gamma_{\rm mix} \equiv [d/dt(T_i - T_{\rm eq})]/T_{\rm eq}$, where $T_{\rm eq}$ is the average of T_x, T_y, and T_z. Furthermore, if $t < \tau$, the trap decay lifetime, the atom density does not change significantly in time t. Typical experimental values are $\Gamma_{\rm mix} = 0.02$/s, $t = 5$ s, and $\tau = 15$ s.

To separate the effects of the background collisions from the intratrap collisions, and also to correct for any interdimensional mixing caused by anharmonicities, all measurements are taken for both high and low density clouds. This requires the density of the cloud to be decreased without changing its size or shape, which is surprisingly difficult to do. However, after unsuccessfully

trying a number of more obvious approaches we succeeded by irradiating the cloud with about 20 mW/cm^2 of blackbody radiation from an incandescent light bulb. After 2 s of this illumination, $\approx 80\%$ of the atoms are removed uniformly from throughout the cloud by being optically pumped to an untrapped Zeeman level. Figure 1 shows the resulting low density (1×10^9/cm^3) growth in the rms size of the trapped atom cloud in the three dimensions, along with a comparison with the higher density (5×10^9/cm^3) results. The collisions with the background gas cause the cloud to expand in all directions; however, it can be seen that this heating is quite isotropic.

From the differences in the slopes of the high and low density data in Fig. 1 we extract the mixing rate for energy to be transferred between the different directions. For the data in Fig. 1 this rate, Γ_{mix}, is 0.022(6) s^{-1}. The elastic collision rate is proportional to this mixing rate, $\Gamma_{el}=\alpha\Gamma_{mix}$, where α is the number of collisions required to spatially mix the different dimensions. Using Monte Carlo methods, we have simulated the collisional dynamics of the trapped atom cloud. We find that α is 2.7.

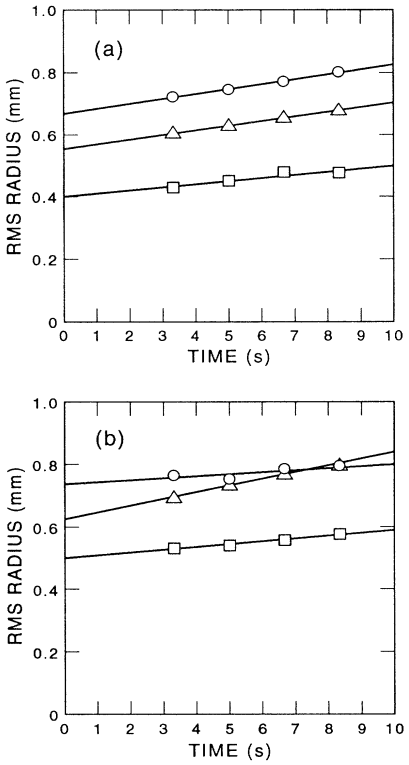

FIG. 1. Measured rms radii of cloud vs time spent in trap for (a) an average density of 1×10^9/cm^3 and (b) an average density of 5×10^9/cm^3. The three sets of data are sizes of three orthogonal views (x, squares; y, circles; z, triangles). The trap oscillation frequencies are $(\nu_x,\nu_y,\nu_z)=(16.2,17.6,9.8)$ Hz, corresponding to a mean atom energy of 67 μK. The lines are least-squares fits; each point displayed is the average of four measurements.

This value for α is essentially the same for wide variations in spring constants, atom cloud sizes, and the form of energy distribution in the cloud. By comparing the observed mixing rate with the mixing rate of a simulated cloud of similar aspect ratio, we determine the experimental cross section.

Several systematic errors can affect our measured density and thus our cross-section value. We believe the systematic error in the measured total number of atoms, determined from total fluorescence measurements, is no more than 15%. Systematic errors in size measurements are less than 5% in any one direction, or less than 15% in volume. The total systematic error in density measurement is less than about 25%.

We measured cross-dimensional mixing at various temperatures by taking data after varying amounts of adiabatic compression of the atoms. In Fig. 2, the measured elastic cross section is plotted as a function of mean energy of the cloud. As the figure shows, the cross section appears to be independent of temperature from 30 to 250 μK. The plotted error bars are determined by statistical scatter in the data.

The intratrap elastic collisions can be characterized by a few partial waves, because of the very low temperatures of the atoms. Furthermore, only even partial waves contribute to spin polarized boson-boson scattering. The threshold energy $E_{th}(l)$ for the appearance of a given partial wave l can be approximated by $U(b)$, the potential energy evaluated at the distance of closest approach b, where $b^2=\hbar^2 l(l+1)/2mE_{th}(l)$. For the Cs-Cs van der Waals potential, $E_{th}(l=2)\approx 150$ μK and $E_{th}(l=4)\approx 1$ mK. Thus for our conditions of less than 250 μK, the elastic cross section will be predominantly s wave and d wave. If there are no nearby resonances, σ_s will be nearly independent of temperature at low temperatures, and σ_d ($l=2$) varies as T^3 [13]. Thus the most plausible interpretation of the lack of temperature dependence in the data is that the d-wave contribution is small and there

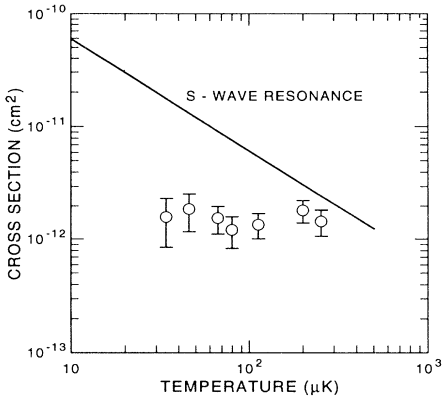

FIG. 2. Log-log plot of measured elastic collision cross section vs temperature. The line represents the maximum resonant value for a purely s-wave cross section at a given temperature.

are no nearby s-wave resonances. From this argument we conclude that the zero-energy s-wave elastic cross section for Cs is $\sigma_s = 1.5(4) \times 10^{-12}$ cm^2, or $5.3 \times 10^4 r_{\text{Bohr}}^2$.

Theoretical calculations of this cross section are plagued by the difficulty that it is extraordinarily sensitive to the exact shape of the interatomic potential. We know of two calculations of this cross section by DeVos and Greene [14] and Tiesinga *et al.* [15] who both obtained values between 10^{-12} and 10^{-11} cm^2. However, these authors examined the sensitivity of the cross section to small changes in the potential, and found that their results were only valid to an order of magnitude. In Ref. [15] it is predicted that there will be large resonances in the cross section for particular ambient magnetic fields. Each of our data points was taken at a different magnetic field because in our apparatus changing the temperature is conveniently accomplished by changing the trapping fields. That we saw no resonances is not surprising since the effect of the predicted resonances is expected to be reduced for our temperatures compared to the 1 μK case considered in Ref. [15].

The primary motivation for this work was to investigate the feasibility of using evaporative cooling of magnetically trapped cesium to reach the temperatures required for Bose-Einstein condensation. Our results lend support to the idea that this is a feasible approach. This is in agreement with the theoretical work of Ref. [15]. In that reference, in addition to calculating the elastic collision rate, the authors also found the Cs-Cs dipole relaxation rate for the state we are trapping and the three-body recombination rate. They determined the dipole relaxation rate to be 1×10^{-15} cm^3/s, which is consistent with (although much smaller than) our upper limit of $< 5 \times 10^{-14}$ cm^3/s, and the three-body rate to be $\langle n^2 \rangle (5 \times 10^{-29}$ cm^6/s). From our Monte Carlo studies we find the criterion for effective evaporative cooling [16] is that $\Gamma_{\text{el}}/\Gamma_{\text{loss}}$ must be greater than 150. Comparing these two loss rates with our measured elastic cross section we find that evaporation should be able to continue to below the BEC transition temperature. Currently the limiting loss process for the trapped cesium atoms is not the cold Cs-Cs interactions, but rather the loss rate from collisions with background gas. This technical obstacle can be overcome simply by improving the vacuum system and increasing the density of the trapped cloud.

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