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Observation of a Zero-Energy Resonance in Cs-Cs Collisions

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We measure the cross section for s-wave collisions of Cs atoms in a magnetic trap. From the relaxation of the atomic cloud towards thermal equilibrium, we infer that the cross section varies as $1/T$ over the temperature range $T = 5-60$ μK. It takes at each measured temperature the maximum allowed value for polarized bosons. This indicates a zero-energy resonance generated by a bound or virtual state less than 5 μK from the dissociation threshold. [S0031-9007(97)03677-6]

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During the past few years ultracold binary atomic collisions have gained a renewed and broad interest since they play a key role in the understanding of the properties of Bose-Einstein condensates [1–3], the ultimate precision of atomic clocks [4], and some experimental tests of time reversal invariance [5]. A detailed knowledge of the atomic collision processes is essential for those applications, either to correct for their effects as in atomic clocks, or to take benefit of them as in evaporative cooling [6], which remains the only demonstrated route to Bose-Einstein condensation of dilute atomic gases.

The case of the cesium atom is of particular interest since it is at the basis of primary time and frequency standards. Collisions between cold ^{133}Cs atoms have already been the subject of several studies, the results of which have been sometimes complementary [4,7,8], sometimes contradictory [9]. In this Letter we investigate the elastic collisions between fully polarized ultracold Cs atoms for temperatures T between 5 and 60 μK. We observe a strong variation of the corresponding cross section σ, with a $1/T$ dependence. For these values of T, we are concerned only with binary s-wave scattering [10]. Collisions with odd angular momenta l (such as p wave) are forbidden for polarized identical bosons, while collisions with even $l \geq 2$ (e.g., d waves) have a negligible effect at these ultralow temperatures. We find that, over the whole temperature range, the measured σ is equal (within the experimental uncertainty) to $8\pi/k^2$, where k is the relative wave vector of the colliding atoms. This result, equal to the maximum allowed value for s-wave scattering, is a signature of a zero-energy resonance [11,12].

The experiments described below consist in preparing an atomic sample in a magnetic trap with a nonthermal distribution. The average energy per atom is selected by using a chirped radio-frequency magnetic field to eject energetic atoms from the trap. We then measure the relaxation time towards equilibrium under the influence of elastic collisions. We finally compare our data with a Monte Carlo simulation of the collisional dynamics of the cloud, from which we extract the value of the cross section for elastic collisions [7,13].

We use a time-averaged orbiting potential (TOP) magnetic trap [14]. It is obtained by superposing a static quadrupole field and a uniform rotating field. Two coils with opposite current produce the quadrupole field, with a magnetic gradient $-b'$ in the x-y (horizontal) plane and $2b'$ along the z (vertical) axis. Two orthogonal pairs of Helmoltz coils induce a horizontal rotating field, with an amplitude B_0. The field zero then rotates on a horizontal circle with radius $R_0 = B_0/b'$. For a particle with a magnetic moment μ antiparallel to the local field $\vec{B}$, the time-averaged potential is minimal at the center of the quadrupole. It is harmonic around this point with spring constants satisfying $\kappa_x = \kappa_y = \kappa_z/8 = \mu b'^2/2B_0$.

To obtain both a long lifetime of the trapped sample and a short loading time, we use a double cell system which has been described in detail elsewhere [15]. In the upper cell, the pressure (essentially due to Cs vapor) is on the order of 10^{-8} torr while in the lower cell, located 70 cm below, it is at least 2 orders of magnitude less. The experimental sequence is as follows: during 2 s we collect $\sim 10^8$ atoms in a magneto-optical trap (MOT) in the upper cell. The trap light and the magnetic field are then switched off; the atoms fall into the lower cell where they are recaptured in a second MOT with 30% efficiency. A further compression, obtained by ramping b' from 10 to 60 G/cm, leads to a peak density of 2×10^{11} cm^{-3} before the light is turned off [16]. Once B_0 is set to 15 G, the atoms are optically pumped into the Zeeman substate $|F = m = 4\rangle$ with a 90% efficiency, using five 40 μs pulses of circularly polarized light synchronized with the field rotation (frequency 5 kHz). For this fully polarized state, μ equals the Bohr magneton. The quadrupole is then ramped up to its maximum value $b' = 125$ G/cm, obtained at a current of 50 A. The resulting trap frequencies are $\nu_x = \nu_y = 24$ Hz and $\nu_z = 66$ Hz and the potential depth, calculated from the center up to the zero field orbit is 260 μK. At this stage 2.5×10^7 atoms are trapped. After some rapid losses ($\sim$5 s) due to the escape of the most energetic atoms which pass beyond the field zero orbit and undergo a flip of their magnetic moment (Majorana transition), we obtain 1.5×10^7 atoms in the TOP, with a peak density

of 1.5×10^{10} cm^{-3} and a temperature of 60 μK. The trap lifetime is 70 s for this cloud, and it reaches 100 s for smaller samples for which Majorana transitions are negligible. At these low atomic densities, losses due to dipolar relaxation and three-body recombination are negligible [17].

The detection is made by an absorption imaging technique. With the TOP trap on, a 40 μs pulse of circularly polarized light propagating along the y axis and parallel with the instantaneous central B field illuminates the atoms. The light is resonant with the closed transition $|6S_{1/2}, F = m = 4\rangle \rightarrow |6P_{3/2}, F = m = 5\rangle$ and its intensity is 10% of the saturation intensity I_s for this transition ($I_s = 1.1$ mW/cm^2). The shadow of the cloud is imaged on the CCD array of a camera. This gives access to the column density $\int n(x, y, z)\, dy$, where $n(x, y, z)$ is the spatial density. We can then deduce the total number of atoms and, assuming a Gaussian spatial distribution with cylindrical symmetry along z, the density $n(x, y, z)$. In this interpretation of shadow images, we take into account the spatial variations of the magnetic field amplitude and the angle between the propagation axis of the imaging beam and the local atomic polarization.

Once the atoms are loaded in the TOP trap, we perform a forced evaporation using a radio-frequency field. This induces transitions between the various Zeeman substates $m = 4 \rightarrow m = 3 \rightarrow \cdots m = -4$ leading to the escape of resonant atoms out of the trap. Because of the spatial variation of the Zeeman shifts the corresponding resonance condition is satisfied on a surface depending on the rf frequency ν. This evaporation surface has the shape of a barrel; it can be approximated by a vertical cylinder of radius R_e such that $g\mu_B(B_0 + R_e b') = h\nu$, where $g = 1/4$ is the Landé factor [6].

This ejection of high energy atoms is performed by sweeping down linearly the frequency ν for 10 s. This duration is short enough that the thermalization of the cloud during evaporation is only partial at our atomic densities. The initial value $\nu_i = 10.5$ MHz is chosen so that the evaporation radius R_e is equal to R_0. The final value ν_f is varied from 9.5 to 6.125 MHz [20]. We then determine the rms widths along x and z, Δx and Δz, by a Gaussian fit of the spatial distributions obtained by absorption imaging. Although a Gaussian spatial distribution is expected only for thermalized clouds, we find that it fits all experimental data well with no appreciable systematic deviation. The resulting clouds have a final total energy per atom $E = 2\kappa_x \Delta x^2 + \kappa_z \Delta z^2$ which we varied between $3k_B \times 53$ μK and $3k_B \times 5.3$ μK by adjusting ν_f. Because of the cylindrical geometry of the evaporation surface the atomic distribution just after evaporation has an ellipticity $e = \Delta x/\Delta z$ smaller than the equilibrium value $2\sqrt{2}$.

Once the cloud is prepared with the desired energy, we stop the rf evaporation and let the cloud thermalize in the TOP potential for an adjustable duration t before taking an image. The evolution of the energy per atom E as a function of t is given in Fig. 1(a) for the three examples $\nu_f = 6.25$ MHz, $\nu_f = 7.75$ MHz, and $\nu_f = 9.50$ MHz. For the two lower values of ν_f, E is remarkably constant, indicating that heating processes due to collisions with the background gas are negligible at this level of accuracy. For clouds with a high initial energy per atom, we observe a slight decrease of E with time. We interpret this phenomenon as a residual evaporation at R_0, which is confirmed by the numerical integration of the trapped atom motion (see below). The temporal evolution of the ellipticity is given in Fig. 1(b), again for the three final evaporation frequencies specified above. We model this evolution using an exponential law, from which we deduce the relaxation time τ_R and the asymptotic ellipticity e_∞. For the smallest cloud, $E/3k_B = 5.3 \pm 0.6$ μK and $n(0) = (7.5 \pm 2.0) \times 10^9$ cm^{-3} and we find $\tau_R = 5$ s. This value increases up to 27 s for the largest cloud, for which $E/3k_B = 53 \pm 2$ μK and $n(0) = (10.0 \pm 2.5) \times 10^9$ cm^{-3}.

To make sure that the relaxation of the ellipticity is due to elastic collisions between trapped atoms and not to anharmonic mixing between the x, y, and z motions, we have reduced the initial atomic density by a factor of 3, keeping a constant temperature. The measured relaxation time is then increased by a factor of 3, within the experimental uncertainty (10% for relative measurements), while it should be constant if the observed relaxation was due to anharmonic mixing. This is confirmed by the fact that the shortest relaxation times are obtained for the coldest and smallest clouds, for which anharmonicity effects play the least role.

The parameter e_∞ ranges between 2.5 and 2.8; the lowest values are obtained for the longest τ_R's. This slight deviation from $2\sqrt{2}$ also appears in the numerical simulation when τ_R becomes non-negligible compared to the lifetime of the trap. In this case, the collision

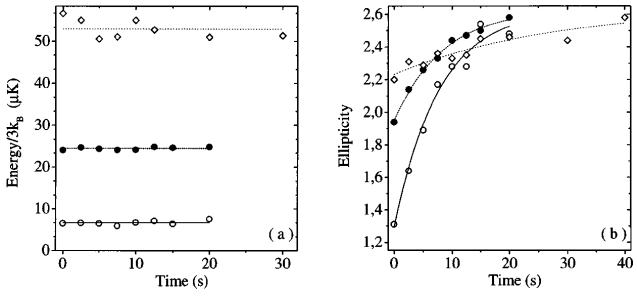

FIG. 1. Temporal evolution of the energy of the trapped sample. The lines are linear fits; (∘) $\nu_f = 6.25$ MHz, $E/k_B = 6.7$ μK; (•) $\nu_f = 7.75$ MHz, $E/k_B = 24.5$ μK; (◇) $\nu_f = 9.5$ MHz, $E/k_B = 53$ μK. (b) Temporal evolution of the ellipticity of the trapped cloud. The lines are exponential fits to the data; (∘) $\nu_f = 6.25$ MHz, $\tau_R = 7.7$ s, $\bar{n} = 2.28 \times 10^9$ cm^{-3}; (•) $\nu_f = 7.75$ MHz, $\tau_R = 8.4$ s, $\bar{n} = 5.51 \times 10^9$ cm^{-3}; (◇) $\nu_f = 9.5$ MHz, $\tau_R = 27.4$ s, $\bar{n} = 3.46 \times 10^9$ cm^{-3}.

rates drop as the number of atoms decreases, leading to a modification of the asymptotic ellipticity.

We now relate the measured value for τ_R to the collision cross section σ between trapped atoms. If σ was constant over the relevant temperature range, one would get $\tau_R \simeq 2.7/\gamma_c$, where the collision rate γ_c equals $\bar{n}\sigma\bar{v}$; the average density is defined by $\bar{n} = \int n^2(\vec{r})\, d^3r / \int n(\vec{r})\, d^3r$ and $\bar{v}$ is $4(k_B T/\pi M)^{1/2}$, where M is the atomic mass. The factor 2.7 results from a Monte Carlo analysis of the relaxation process [7,21]. We have therefore plotted in Fig. 2 the quantity $(\bar{n}\bar{v}\tau_R)^{-1}$ as a function of temperature, which should be a constant (equal to $\sigma/2.7$) in the hypothesis of a constant σ.

The results in Fig. 2 clearly show that $(\bar{n}\bar{v}\tau_R)^{-1}$ varies strongly with temperature. We interpret this as a signature of a rapid increase of σ when the relative velocity $v_r = 2\hbar k/M$ of the colliding atoms decreases. For s-wave scattering, this effect occurs when the atom-atom interaction potential is such that the last bound state is close to the dissociation limit, or when there exists a virtual state close to this limit. In both cases, the cross section σ is maximal for a zero colliding energy [11,12] and it varies as

$$\sigma(k) = \frac{8\pi a^2}{1 + k^2 a^2}, \tag{1}$$

where a is the scattering length.

To check this hypothesis of resonant scattering we have performed a numerical simulation of the evolution of the atomic cloud, assuming the maximal cross section for s-wave scattering of polarized bosons $\sigma_{\max}(k) = 8\pi/k^2$. In the simulation, the residual evaporation at R_0 mentioned above is included and the collisions are treated using the method described in [21]. At each time step δt, the atomic positions are discretized in cubic cells whose volume δV is chosen small enough in order to limit the average number of atoms per cell to a value much below 1. If two atoms are localized in the same cell at a given time, a collision may occur with a probability $\delta t \sigma_{\max}(k) v_r/\delta V$. The relative velocity after collision is chosen randomly with an isotropic distribution, as required for s-wave collisions. We use Gaussian distributions for the initial positions and velocities, with rms values equal to the experimental ones. We fit the temporal evolution of the ellipticity determined from the rms sizes in x, y, and z by an exponential law, as for the experimental data.

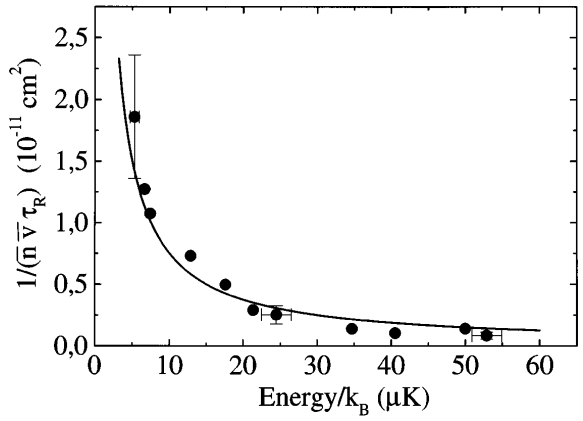

FIG. 2. The experimentally determined quantity $(\bar{n}\bar{v}\tau_R)^{-1}$ (full circles) is plotted as a function of the average collision energy. The solid line represents the result of a Monte Carlo simulation without any adjustable parameters assuming the maximum cross section for s-wave scattering.

The result of the simulation is plotted as the solid line in Fig. 2. We find $(\bar{n}\bar{v}\tau_R)^{-1} \sim 8.310^{-11}/T\ \mathrm{cm}^2$, where T is measured in μK; this can be written $\tau_R \sim 10.7/\gamma_c$, where $\gamma_c = 128\bar{n}\hbar^2/\bar{v}M^2$ for this velocity-dependent cross section. The reason for which the thermalization now requires on average 10.7 collisions instead of 2.7 is that most collisions now occur between atoms having a small relative velocity, which has little impact on the relaxation towards equilibrium.

The experimental data are clearly in good agreement with these predictions. We therefore observe a zero-energy resonance corresponding to either a virtual state or to a bound state whose binding energy is smaller than our lowest temperature 5 μK [22]. The scattering length a is negative in the first case and positive in the second. Our experimental results allow us to put a lower bound on the absolute value $|a|$; if we were to interpret the thermalization of our coldest cloud as being due to a constant cross section, we would get $\sigma_0 = 5 \times 10^{-11}$ cm^2, corresponding to a scattering length $a_m = \pm 260 a_0$, where a_0 is the Bohr radius. Since the set of data sketched in Fig. 2 indicates that the product $\bar{n}\bar{v}\tau_R$ has not yet reached its zero temperature value, we can conclude that the real scattering length satisfies $|a| > |a_m|$. This value is notably larger than those measured for other fully polarized alkalis, e.g., $110a_0$ for ^{87}Rb [24] or $-27a_0$ for ^{7}Li [25].

We now briefly compare our measurements with previous results on collisional effects for ultracold Cs atoms. Using a technique similar to the present one, Monroe *et al.* [7] have found for $|F = 3, m = -3\rangle$ atoms a cross section $\sigma = 0.15 \times 10^{-11}$ cm^2 independent of T in the range 30–250 μK. This is of the same order as our highest temperature data. At a much lower temperature (0.9 μK), Gibble *et al.* [8] have measured the relaxation of a narrow velocity distribution of atoms in the $|F = 3, m = 0\rangle$ state colliding with atoms distributed among the $|F = 4, m\rangle$ states, resulting in $\sigma = 4 \times 10^{-11}$ cm^2. That experiment dealt with unpolarized atoms, for which Bose statistics plays little role. Therefore this result is also consistent with our low temperature data since, for polarized bosonic atoms, the cross section is increased by a factor of 2 with respect to distinguishable particles. Although a detailed comparison between those various results is made difficult since they deal with different ground state sublevels, such an increase of the elastic cross section (a factor of 27 between [7] and [8]) may be understood in view of our

observation of a zero-energy resonance. More indirect measurements, based on collisional frequency shifts in an atomic fountain [4,10], have led to $-200a_0 < a < -1100a_0$ for atoms in the $|F = m = 4\rangle$ state [10] (see also [26]), which is consistent with our results.

To summarize we have observed a zero-energy resonance in the s-wave scattering of fully polarized cesium atoms. The cross section increases by a factor of ~ 10 between 50 and 5 μK, reaching the universal maximum value $\sigma = 8\pi/k^2$ for polarized bosons. This rapid variation should have important consequences on the evaporative cooling of a cesium cloud down to the degenerate regime. First it should facilitate the achievement of the runaway evaporation regime [6], in which the collision rate stays at least constant as the temperature of the cloud decreases. Also the sign of a is an important feature for the stability of a Bose-Einstein condensate [27]. It is noteworthy that the existence of either a virtual or bound state very close to the dissociation limit should facilitate the control of both the size and the sign of the scattering length by weak, off-resonant laser light [28–30].

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