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Simultaneous trapping of two different atomic species in a vapor-cell magneto-optical trap

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We have produced a magneto-optical trap that simultaneously confines two different atomic species: sodium and potassium. A measurement of the sodium trap loss rate constant due to collisions with cold potassium atoms was performed. We extract this rate constant by measuring the temporal behavior of the loading process of the sodium trap in the presence and absence of cold potassium. The constant that is obtained can be qualitatively explained using simple existing models. Future applications of simultaneous trapping are discussed.

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Very early in the development of optical traps, it was recognized that several novel collisional effects would be very important and would contribute to a better understanding of the atom-atom interactions. Contrary to the usual atomic collisions, at low temperatures the interaction times are very long and comparable to spontaneous emission times. Collisions become very sensitive to the long-range interatomic potentials and can be highly quantum mechanical in nature. Even more important is the role absorption and emission of radiation play: the probability of absorbing or emitting a photon during the collision time is no longer negligible. Therefore, the dynamics of the collisional process depends greatly on the internal states of the colliding atoms [1].

The samples of cold atoms are usually provided by a magneto-optical trap (MOT) [2], in which several recently reported effects have been observed [3–8]. All these experiments, and most of the theories developed to date, have in common the fact that they deal with a single atomic species. The first experimental "variation on this theme" has been performed by W. Süptitz *et al.* [9]. They have simultaneously cooled and trapped two different rubidium isotopes and measured a cross-isotope collisional rate. An even stronger variation would consist of studying cold collisions involving different atomic species. That could open up new and exciting possibilities. For example, sympathetic cooling [10–12] of neutral atoms, where one species is cooled by interaction with a second one, should be possible. High resolution studies of molecular bond formation involving different alkali-metal atoms are also of fundamental interest.

In this paper we present an experiment on the simultaneous magneto-optical trapping of two different atomic species, and report on the observation of cold collision effects involving different alkali-metal atoms. We confine simultaneously (in space and time) cold atoms of sodium and potassium and investigate the rate constant for collisional trap loss due to a process involving different species. The process is interpreted as a two-body collision and measured through the transient loading of the trap.

Our magneto-optical trap operates in a room temperature glass vapor cell that contains separate sodium and potassium reservoirs. The initial vacuum in the cell is made by using a turbo molecular pump that is subsequently valved off from the system, and the operational vacuum ($P<10^{-8}$ torr) is maintained by a 30-l/s ion pump. Atoms are loaded into the trap from the low-velocity tail of the Maxwellian distribution present in the vapor. Sodium and potassium reservoirs, with independently controlled temperatures, are located in one of the arms of the glass chamber. Under our present experimental conditions, the reservoir temperatures are 100 °C for sodium and 20 °C for potassium, providing a constant flux of atoms to be trapped. The partial pressures of sodium and potassium are thus estimated to be of the order of 10^{-9} and 10^{-8} torr, respectively. Control of the partial pressures (via the reservoir temperatures) is important because of the considerably different vapor pressures these elements have at the same temperature. If the partial pressures were too different, the excessive background vapor of one species would compromise the performance of the other species' trap. Another matter of concern could be the eventual condensation of sodium atoms on the colder potassium reservoir. Such effects have not been observed in our system.

A general schematic view of the apparatus is presented in Fig. 1. The MOT layout consists of three mutually orthogonal pairs of counterpropagating laser beams (for each species) with opposite circular polarizations, intersecting at the center of a quadrupolar magnetic field. The magnetic field is created by a pair of coils in an "anti-Helmholtz" configuration. The z-axis magnetic-field gradient can be as high as 40 G/cm, and half of that in the xy plane. Two windows along the z axis (vertical) and eight windows in the xy plane provide access for the trapping laser beams, for the vacuum pump, and for observation.

The laser beams used to trap atoms are provided by a ring-dye laser (Coherent 699) and by a Ti:sapphire laser (Coherent 899). The dye laser operates close to the sodium $3S_{1/2}(F=2)\rightarrow 3P_{3/2}(F'=3)$ transition ($\lambda_{Na}=589$ nm; see Fig. 2), which is the cycling transition for the trapping of Na atoms. The Ti:sapphire laser operates tuned just below the $4S_{1/2}(F=2)\rightarrow 4P_{3/2}$ (manifold) transition of potassium ($\lambda_K=766$ nm; see Fig. 2). Mechanical shutters placed in the beams allow us to block or unblock individual lasers. Before entering the cell, small fractions of the laser beams are diverted to Na and K saturated absorption cells that provide reference transitions used to correct for slow drifts of the laser frequencies.

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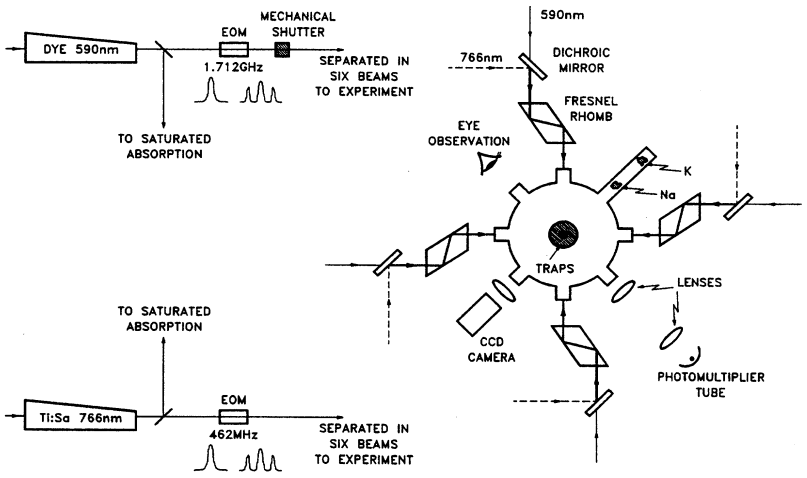

FIG. 1. Schematic view of the experimental apparatus. The z axis (vertical) is perpendicular to the paper. On the left-hand side are the lasers responsible for sodium and potassium trapping with their respective electro-optic modulators (EOMs) and the mechanical shutter used to interrupt the dye-laser beam when needed. On the right-hand side is the main glass chamber containing the sodium and potassium reservoirs. The two lasers are combined before each window with dichroic mirrors. The appropriate circular polarization is produced with achromatic Fresnel rhombs (FR). Three of the windows on the xy plane are used for observation: with a photomultiplier tube, a CCD camera, and the naked eye. Anti-Helmholtz coils have their axis parallel to the z axis and are not shown in the figure. The traps sketched in the figure are (obviously) not to scale.

In order to prevent population loss from the main optical transitions into the other hyperfine levels, repumping frequencies are introduced using sidebands generated by electro-optic modulators placed along the beam paths (as indicated in Fig. 1). Level diagrams showing the relevant transitions and frequencies for trapping and repumping are presented for both atoms in Fig. 2. The beams from the dye and Ti:sapphire lasers are combined with dichroic mirrors ($\sim 100\%$ transmissivity at 589 nm and $\sim 100\%$ reflectivity at 766 nm) and enter the main cell collinearly. Circular polarization is achieved by means of Fresnel rhombs (FR) that are achromatic $\lambda/4$-retarding plates. Contrary to most existing MOTs, we use six independent equal intensity beams instead of three retroreflected beams [2]. This is due to the unavailability of an efficient antireflection coating for both wavelengths. Reflection losses on the glass windows of the cell would result in significant intensity imbalances in the case of retroreflected beams.

We observe trapping of each individual species, or of both together, when the lasers are tuned as indicated in Fig. 2. For sodium, optimum trapping is achieved when the main frequency is tuned ~ 10 MHz below the $3S_{1/2}(F=2) \rightarrow 3P_{3/2}(F'=3)$ transition and the repumper is resonant with the $3S_{1/2}(F=1) \rightarrow 3P_{3/2}(F'=2)$ transition. The potassium trap is optimized when the main laser is tuned ~ 40 MHz to the red of the $4P_{3/2}$ excited-state manifold while keeping a fixed 462-MHz difference between the sideband and carrier frequencies (see diagram in Fig. 2). These are the laser frequencies used for the measurements described further below.

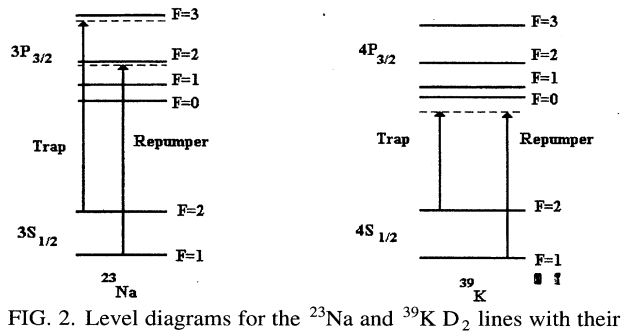

FIG. 2. Level diagrams for the ^{23}Na and ^{39}K D_2 lines with their respective hyperfine structures. The wavelengths for Na and K are $\lambda_{Na}=589$ nm and $\lambda_K=766$ nm, respectively. Ground-state hyperfine splittings are 1.77 GHz for Na and 462 MHz for K. The Na $F=3$, $F=2$ excited-state splitting is 60 MHz. Trapping and repumping transitions for both atoms are indicated in the diagrams. Since the excited-state hyperfine structure for K is not resolved, both trapping and repumping frequencies are to the red of the whole manifold.

The trap shape and density are determined by imaging its fluorescence onto a calibrated photomultiplier tube (PMT) while measuring the dimensions with a charge-coupled-device (CCD) camera. To perform separate trap measurements for each alkali-metal atom, passband optical filters are placed in front of the camera and PMT. An intensity profile of the spatial atomic distributions, as observed by the camera, is shown in Fig. 3. The sodium atomic cloud is located within the larger potassium cloud. For a magnetic-field gradient of 30 G/cm, total dye-laser intensity of 40 mW/cm^2 ($1/e$ of the Gaussian intensity profile ~ 6 mm), and total Ti:sapphire laser intensity of 240 mW/cm^2 ($1/e$ of the Gaussian profile ~ 5 mm), we measured the number of trapped potassium atoms to be $N_K \simeq 9.5\times 10^8$ atoms, with a density $n_K=(4\pm 2)\times 10^{10}$ cm^{-3} and the number of sodium to be $N_{Na}\simeq 5\times 10^7$ atoms with a density $n_{Na}=(7.4\pm 3.5)\times 10^9$ cm^{-3}. The high intensity of the potassium laser helps to compensate for the large detuning necessarily used for trapping.

To investigate the cross-species cold collision effects we have chosen to measure the loading of the sodium trap in the presence of the trapped cloud of cold potassium. This choice was due to the fact that in the present experimental conditions the sodium trap is completely surrounded by trapped potassium, in such a way that we are sure all the cold sodium atoms are exposed to interaction with cold potassium. As the sodium trap is loaded, the equation that determines the total number of trapped sodium atoms (N_{Na}) as a function of time can be written as

$$\frac{dN_{Na}}{dt} = L - \gamma N_{Na} - \beta n_{Na} N_{Na} - \beta' n_K N_{Na} . \qquad (1)$$

Here L is the loading rate, γ is the loss rate due to collisions between the trapped Na atoms and the hot background

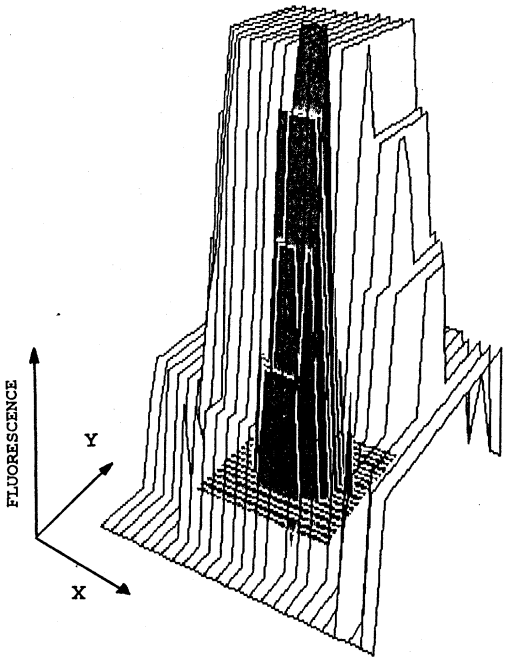

FIG. 3. Three-dimensional profiles of Na and K traps as captured by the CCD camera. The z coordinate is proportional to the traps' fluorescence. The Na trap is smaller and localized inside the K trapped cloud. Typical trap volumes are $V_{Na} \sim 6 \times 10^{-3}$ cm^3 and $V_K \sim 2.5 \times 10^{-2}$ cm^3. The saturation observed in the fluorescence from the K trap is shown here only for the purpose of clarity. The real peak fluorescence from the K trap is about two times larger than the one for the Na trap.

gas composed mostly of thermal Na and K, β is the rate constant for trap loss due to cold collisions between trapped sodium atoms, and β' is the loss rate constant due to cold collisions involving trapped sodium and trapped potassium. Our interest here is to measure β'.

As observed by T. Walker and co-workers [13] for a trap of cesium atoms and confirmed by us for sodium [14], trap loading proceeds basically at constant density, i.e., as the number of atoms increases the volume expands so that the density in the trap remains unchanged. As a result, the solution of Eq. (1) can be written as

$$N_{Na} = N_0\{1 - \exp[-(\gamma + \beta n_{Na} + \beta' n_K)t]\}, \qquad (2)$$

where N_0 is the number of sodium atoms corresponding to the steady-state solution of Eq. (1). Therefore, by measuring the fluorescence from the Na trap during the loading process and fitting the experimental data to Eq. (2), we can determine the value of $\gamma + \beta n_{Na} + \beta' n_K$. We repeat this procedure in the presence and in the absence of trapped potassium atoms and the measured difference provides the value of the term $\beta' n_K$. We "turn off" the potassium trap by detuning the Ti:sapphire laser a few linewidths to the blue of the optimum trapping condition. In this way we can be sure that the measured cross-collisional effect is not due to the presence of the strong Ti:sapphire laser. Using the measured value of the potassium density in the region of the sodium trap, we extract the value of β'.

We have determined $\beta' n_K = (0.11 \pm 0.02)$ s^{-1} in the optimum conditions described previously, hence $\beta' = (3.0 \pm 1.5) \times 10^{-12}$ cm^3/s. This value is the result of 20 independent measurements that were averaged. For the same operating conditions, cold collisions involving only sodium atoms lead to a loss rate $\beta = (3 \pm 1) \times 10^{-11}$ cm^3/s [14], much larger than β'.

The main mechanisms involved in collisional trap loss arise from collisions between a ground-state and an excited-state atom [15]. For homonuclear collisions, the excited–ground-state interaction is a long-range C_3/R^3 potential (R is the internuclear separation and C_3 is a constant) and, therefore, the process starts at a large internuclear separation. In the case of heteronuclear collisions, the excited–ground-state interaction has a C_6/R^6 dependence [16], being significant only at shorter distances.

Two different processes may lead to trap loss in a ground–excited-state collision: fine-structure changing and radiative escape. The fine-structure changing collision results in the excited atom changing its fine-structure state. In the case of sodium, collisions between a ground-state atom and an excited-state sodium atom in the $3P_{3/2}$ level may result in an exoergic transition to the $3P_{1/2}$ level, with the concomitant increase of 17 cm^{-1} in kinetic energy. In the case of an excited-state potassium atom colliding with a ground-state sodium atom, the fine-structure change of the potassium atom would result in a release of 58 cm^{-1} into kinetic energy.

The radiative escape process is essentially a free-free molecular transition in which some fraction of the final ground-state atom pairs possess enough kinetic energy to escape from the trap. The kinetic energy is gained as the atoms "roll down" the attractive interatomic potential.

In order to gain enough energy to escape from the trap before spontaneous emission takes place, the Na-K pair has to be excited much closer than the Na-Na pair, because of the shorter range of the Na-K potential. Since the number of pairs at a distance R varies as R^2, the collisional trap loss in the Na-K system is expected to be smaller than in the Na-Na or K-K system. This explains, qualitatively, the difference observed between β and β'.

We carried out a simple calculation using the well-known Gallagher-Pritchard model [15]. Taking the potential constants for Na-Na* (* refers to an excited-state atom) as given by [15] and for Na-K* as in Ref. [16], a calculation was made to provide only the relative values between the trap loss rates for the Na-Na and Na-K systems and not the absolute values of the rate constants. The result of the calculation shows a relative value between the two collisional loss rates $\beta' \approx 0.2\beta$. Even though we are using a very simple classical model, the predicted relative value is in good agreement with the observations. We have only considered the Na-K* potential because we have not found information about the Na*-K potential. A more elaborate calculation, based on the optical Bloch equations formalism [17], is necessary in order to have a more reliable quantitative comparison between β and β'. We hope this present experiment will stimulate future theoretical work in cold collisions involving different species.

Crossed-species cold collisions can be applied to the realization of sympathetic cooling of two neutral trapped species. Cooling one species below the temperature imposed

by laser cooling can be achieved by sympathetic cooling with another species that cools to a lower temperature. Sympathetic cooling of a fermionic species by an evaporatively cooled bosonic species [18] may be the best strategy for creating a weakly interacting degenerate Fermi gas if direct evaporative cooling of the fermionic species is not possible due to the absence of s-wave collisions at low temperatures. Sympathetic cooling has been successfully demonstrated for Hg^+ and Be^+ ions in a Penning trap [19]. With this present demonstration of simultaneous confinement of cold atoms in a MOT we open the possibility of sympathetic cooling with neutral species. In this case, simultaneous trapping in a MOT would be a first step, followed by pure magnetic trapping. By detuning one of the trapping lasers, in the first step, we could vary the atomic temperature of the associated species. From the present experiment, we have estimated [using the γ term in Eq. (1)] the elastic cross section of the Na-K system to be $(3.8\pm 2)\times 10^{-13}$ cm^2. This cross section refers to collisions between cold Na atoms with room temperature K atoms. Even though we do not have direct access to the elastic cross section for collisions between cold atoms of both species, we assume that it should not be smaller than this value because of the higher sensitivity cold collisions have to long-range interactions. If we combine in a magnetic trap Na and K with a potassium density of about 10^{11} atoms/cm^3 and consider a relative velocity of 100 cm/s, Na-K thermalization should happen in about 0.25 s. Magnetic trapping lifetimes that are longer than these are already perfectly achievable in cells [20], allowing the observation of thermalization. Detection can be made by monitoring the final spatial atomic distribution. The necessary modifications of our experimental setup, for this specific experiment, are presently being made.

A second experiment planned is the observation of photoassociation [21] in the Na-K system, similar to previous work done for other alkali-metal atoms [22,23]. Photoassociation refers to a process in which the incoming colliding atoms in a relatively flat ground-state potential absorb a photon and populate an attractive state, such as Na-K*. The force arising from this attractive potential accelerates the particles together, and they can subsequently decay to a bound state of the Na-K potential. This process results in an increase of trap loss. Observation of the decrease in the trap fluorescence as a probe laser scans through the bound states' resonances allows one to obtain the molecular spectrum [22,23]. In order to see this effect in Na and K, it will be necessary to increase the atomic densities. For this purpose, we are currently preparing a dark MOT [24] for the two species.

In conclusion, we have demonstrated simultaneous magneto-optical trapping of different atomic species and measured the first effects due to cross-species cold collisions. A simple model provides reasonable agreement with the obtained results. This experiment represents a starting point for a new series of studies in the world of ultracold matter.

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