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# Coherent population trapping states with cold atoms in a magnetic field

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**Abstract**

Using potassium atoms cooled with a MOT, ground-state hyperfine coherent population trapped (CPT) states were prepared in a magnetic (**B**) field, and the behavior of CPT states was experimentally studied. We carefully measured the preparation of the CPT state as a function of time and the CPT signal as a function of laser power. The experimental CPT signal linewidth was approximately proportional to the square root of laser intensity in the range of parameters studied, and limits of this relation were explored theoretically.


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*Keywords:* Coherent population trapping; Magneto-optical trap

## 1. Introduction

Atomic coherent population trapping (CPT) states have been found for more than twenty years and have been widely studied both theoretically and experimentally [1]. Laser–atom interactions produce a coherent superposition of states that does not absorb light. Experimental studies have mainly been carried out with atomic beams [2,3] and cells [4,5], which are mainly suited for the study of short time behavior. To study the long time behavior, the main difficulties associated with atomic beams or cells are the short interaction time caused by atom velocity, and decoherence effects caused by collisions. To overcome decoherence effects caused by the collision between atoms and the sample cell wall, cells with antirelaxation paraffin coatings were adopted [6]. Sample cells filled with high pressure buffer gas were used to increase the laser–atom interaction time by collisions between sample atoms and the inert gas [7]. With weaker laser power, narrower CPT spectral lines can be obtained. Narrow CPT spectral lines have been obtained by Brandt et al. [8] (42 Hz FWHM) and Erhard et al. [9] (28 Hz) with cells filled with buffer gas. With high pressure buffer gas, collision broadening and shifts will affect measurement accuracy in high resolution spectroscopy.

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These difficulties can be avoided by using trapped cold atoms, which allow a study of CPT long time behavior in a clean environment. The longer optical pumping times are useful in practice for the full preparation of the coherent state while removing incoherent populations. Using $D_1$ light, the incoherent populations are fully pumped away to $M_F = F$, after which the atoms no longer absorb light for a completely different reason, angular momentum conservation. We can then make a straightforward quantitative test of the predictions without considering intermediate steps associated with Doppler and collision effects.

There have been applications of trapped cold atoms in CPT studies in recent years [10]. In the present paper we report our result of studying CPT behavior in a weak **B** field with our MOT system. The atoms are cooled and then the MOT light and quadrupole **B** fields switched off, except for an applied uniform **B** field and the $D_1$ light creating the coherence. We compare our results with our corresponding theoretical calculation.

## 2. Calculation

Our theoretical calculation is based on a semi-classical approach using the density operator formalism, i.e., the standard optical Bloch equations with the phenomenological spontaneous decay term $R(t)$

$$\left(\frac{\mathrm{d}}{\mathrm{d}t}\right)\rho(t) = \frac{-1}{\mathrm{i}\hbar}[H(t), \rho(t)] + R(t). \qquad (1)$$

We use the expressions of Tremblay and Jacques [11]. Because both of our frequencies come from one laser, then were frequency shifted by two independent RF sources into two frequencies, we assume that the contribution of the laser linewidth to the ground-state relaxation rate vanishes. We observed short time jitter of the RF sources of several hundred hertz, so that a 500 Hz linewidth from RF sources are included in the ground-state relaxation rate $R(t)$ (see [1], Eq. 2.37). The external **B** field is included in Zeeman shifts of the magnetic sublevels but the wave functions are left unperturbed (perturbations of $\rho_{ij}$ are less than 0.06% at 1.6 G). Assuming both $\nu_1$ and $\nu_2$ are perfect $\sigma^+$ polarized laser beams, and considering the narrow linewidth of the diode laser, we ignore Zeeman coherences and excited-state hyperfine coherences, so that only ground-state hyperfine coherences were considered in the calculation. The calculation was carried out by numerically solving the density matrix equations, i.e., the 45 real coupled differential equations for the 15-level system of Fig. 1. (The $4P_{1/2}$ $M_F = -2$ state has no interaction with the laser and was not included.) All calculations were made with initially isotropic ground-state populations.

Similar to [2], in the experiment we use two right circularly polarized laser beams ($\nu_1$ and $\nu_2$ in Fig. 1) along the **B** direction to make $\sigma^+$ transitions. Classically, if there were no coherent trapping effect, this would pump all atoms to the $4S_{1/2}$ ($F = 2$, $M_F = 2$) state. However, when the two laser beams are phase related and have precisely the right relative frequency, some atoms are trapped in other states by hyperfine coherent trapping. Our calculation reproduces the expected result that when $B \neq 0$, with a $B$ field as weak as 0.05 G the hyperfine coherent effect will only trap atoms on a pair of $M_F$ sublevel states with energy splitting $\Delta E_{M_F}$ equal to $h(\nu_1 - \nu_2)$ of the pumping laser. Fig. 1 shows

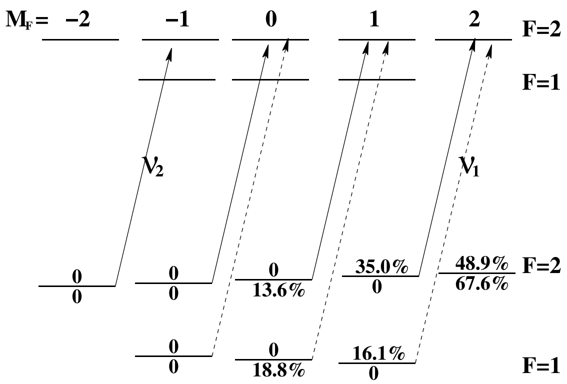


Fig. 1. Calculation of $^{41}$K CPT was made with parameters: $B = 1.51$ G; laser intensity $I(\nu_1) = 145$ μW/cm$^2$, $I(\nu_2) = 200$ μW/cm$^2$; both linewidths are 0.2 MHz; pumping time is 625 μs. The calculated population distribution is indicated: above the line of the state is the population with laser frequencies satisfying $h(\nu_1 - \nu_2) = \Delta E_1$; while under the line is for $h(\nu_1 - \nu_2) = \Delta E_0$. (For $h(\nu_1 - \nu_2) = \Delta E_{-1}$, the population distribution is 3.5% at $|2, -1\rangle$ and 14.4% at $|1, -1\rangle$, with 82.1% left at $|2, 2\rangle$.)

examples of the population distributions from our calculation when $h(\nu_1 - \nu_2) = \Delta E_{M_F}$ with $M_F = 0$ and +1 at $B = 1.51$ G.

## 3. Experimental details

We study CPT using atoms cooled with a standard configuration six-beam MOT with the three incoming beams retroreflected. The MOT cell is a dryfilm-coated pyrex vapor cell, with potassium supplied by a SAES Getters alkali metal dispenser. The vacuum-limited trap decay time is approximately 10 s. From a master diode/slave tapered amplifier laser followed by AOMs for frequency shifting, the total power of the $D_2$ trap beams is about 50 mW. We have measured that the CPT linewidth and the fraction of atoms in the coherence do not change when the number of atoms changes by a factor of 2.5. So, with approximately $10^6$ atoms trapped in a 0.2 cm diameter cloud, we remain in a density regime where radiation trapping effects are negligible [5]. Sub-Doppler cooling for $^{41}$K is difficult to achieve, because of the relatively narrow hyperfine splitting [12], and we have estimated the MOT atom temperature from recapture measurements to be ~600 μK.

The nonzero **B** field condition for efficient optical pumping is realized by attenuating the two retroreflected $D_2$ trapping beams of the MOT that are in the horizontal plane. Then the trapped atom cloud's equilibrium position is moved away from the MOT center to nonzero **B** field. An additional uniform **B** field from Helmholtz coils is then applied along the axis to move the atoms back to the original MOT center [13]. This places the atoms in the original position, but now at nonzero and known **B** field. The experimental process is to turn the MOT and $D_1$ beam on and off alternately with a 20 ms duty cycle, in which the MOT quadrupole **B** field and $D_2$ trapping beams are on for 18 ms for trapping $^{41}$K. During the 2 ms off time, the first millisecond is left for the quadrupole **B** field to completely decay to zero. The $D_1$ laser is then turned on during the second millisecond to interact with "free" atoms for the coherence study. The $D_1$ light is from a diode laser independent from the MOT system, which is frequency stabilized by

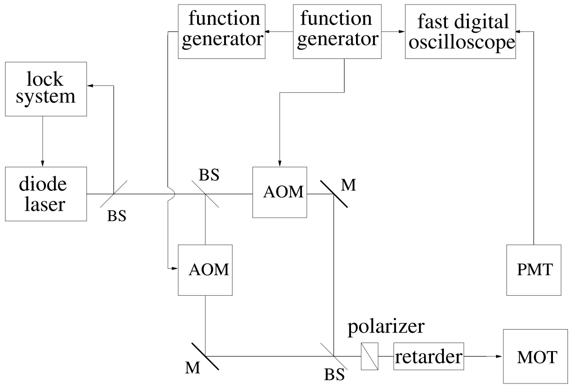


Fig. 2. Schematic of the experimental apparatus. M, mirror; BS, beam splitter. A liquid crystal variable retarder (Newport/Meadowlark Optics, model 932) was used as $\lambda/4$ waveplate to convert polarization from linear to circular. Two AOMs are used to shift laser frequency by ±127 MHz to form $\nu_{1,2}$.

locking to a saturated absorption spectral line. Fig. 2 is the setup of the coherence pumping system. A PMT with a $D_1$ interference filter is used to monitor the fluorescence produced by the $D_1$ beams.

## 4. Results and discussion

Fig. 3 is a typical curve recorded in our experiment, which was recorded with $h(\nu_1 - \nu_2) = \Delta E_0$. At $t = 0$, the $D_1$ light is turned on. Fluorescence occurs as the atoms are optically pumped, producing the first peak. The fluorescence decreases to close to zero as the atoms are mostly pumped to the $F = 2$, $M_F = 2$ substate, which does not absorb $D_1$ light. Then at $t = 625$ μs, the $\nu_1$ laser is switched off. The hyperfine coherence is destroyed, and the atoms which were coherently trapped predominantly in the $F = 2$ $M_F = 0$ state then fluoresce as they undergo hyperfine optical pumping, producing the second "CPT peak". From the relative sizes of the theoretical and experimental "CPT peak", we deduce in this figure that ≈72% of the expected coherence population is achieved. We attribute the longer tail of the experimental first peak – which is mostly due to classical optical pumping processes and unrelated to CPT – to nonuniform laser intensity over the trap cloud.

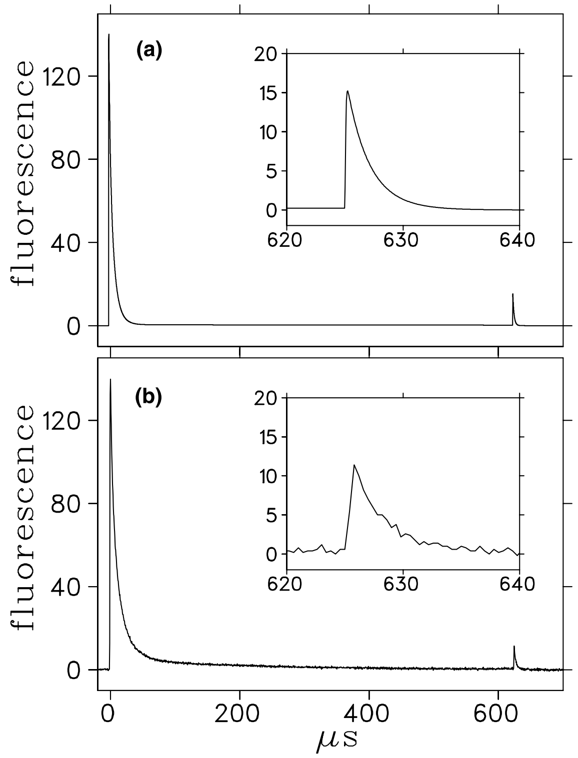


Fig. 3. Comparison of calculated curve in (a) with experimental recorded curve in (b) (the inset is the second peak for detailed comparison). Experimental curve was recorded with conditions: $B = 1.51$ G, $I(\nu_1) = 0.16$ mW/cm$^2$, $I(\nu_2) = 0.29$ mW/cm$^2$ (the laser intensities were from fitting experimental data); $\nu_1$ is off at 625 μs; $h(\nu_1 - \nu_2) = \Delta E_0$. In the experiment every curve was obtained by recording twice, first with cold atoms trapped in the MOT, then a (small) background without cold atoms trapped in the MOT was recorded and subtracted. For all the calculations in this paper the laser linewidth is 0.2 MHz and the RF source linewidth is 500 Hz. Other parameters of (a) are from experiment. The main peak of the calculated curve has been normalized with the experimental one.

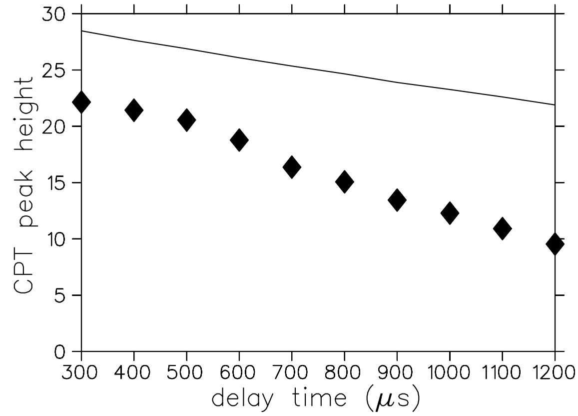


Fig. 4. Diamonds are experimental data recorded at condition: $B = 1.51$ G, $I(\nu_1) = 0.18$ mW/cm$^2$, $I(\nu_2) = 0.30$ mW/cm$^2$; $h(\nu_1 - \nu_2) = \Delta E_0$. $I(\nu_1)$ was switched to zero at the "delay time". The theoretical curve was calculated with experimental parameters and normalized to the first fluorescence peak of the experimental one.

It is seen that after 600 μs the recorded curve in Fig. 3 is approximately constant with time, which means most of the atoms have been optically pumped. With the experimental parameters, the corresponding calculated curve is also shown.

Fig. 4 compares the theoretical curve and experimental recorded results (diamond) of the CPT peak amplitude – proportional to the percentage of atoms trapped in the hyperfine coherence – as a function of the time at which the $\nu_1$ laser was switched off. The decrease of the calculated population of the hyperfine resonance with time is because of the assumed 500 Hz RF source linewidth. The faster decay of the experimental CPT peak amplitude with delay time, and the relatively weak absolute size of the CPT signal, are the main disagreements between experiment and calculation. (A trivial reason for the smaller CPT peak is that the pumping laser will heat the free atoms during the pumping process which causes some of atoms to have left the view of PMT when CPT signal is recorded; this effect was measured observing the decreasing fluorescence of the already pumped atoms with both frequencies still on, and a small correction has been made to the experimental data shown.)

Possible explanations for the shorter experimental CPT lifetime compared to theory in Fig. 4 lie in imperfect experimental conditions. The shape and size of our Helmholtz coils is imperfect, and atoms see a $B$ field with approximately 0.01 G inhomogeneities. This is consistent with our observation that the ratio of experimental to theoretical population of the $M_F = \pm 1$ coherences, which are sensitive to first-order Zeeman shifts, are 37% and 40%, respectively, compared to 72% for $M_F = 0$. Other possible reasons include: imperfect circularly polarized laser light, imperfect overlap of $\nu_1$ and $\nu_2$ laser beams, and laser power variations across the trap cloud.

As has been mentioned, the CPT linewidth is closely related to the laser intensity, and this has been studied by a number of authors. When CPT is generated by laser beams with two different frequencies, by fixing laser power at one frequency and varying the other, the CPT linewidth depends linearly on the power variation [8,9]. Vanier et al. [14] deduced in their study that the CPT linewidth depends linearly on the power variation of both frequencies, while Javan et al. [15] indicated that under certain conditions, the linewidth is proportional to the square root of laser intensity of one frequency and is independent of Doppler width, which is experimentally supported by Ye and Zibrov [16].

At fixed laser powers, we measured the CPT linewidth by detuning one laser frequency with fine steps and recording the corresponding CPT peak amplitude. Fig. 5 shows the comparison between the experimental result and the calculation at different laser intensities. The agreement is good. In the experimental regime explored here, the linewidth is approximately proportional to the square root of the laser intensity.

We can show this more precisely by making calculations with different laser intensity $I$ including the condition that the laser intensities of both frequencies change simultaneously $I = I(\nu_1) = cI(\nu_2)$, with $c$ constant. In the configuration of Fig. 1, the calculated linewidth of the CPT signal is proportional to the square root of laser intensity over a wide range, as long as the intensity is not strong enough to broaden the CPT signal to the point that it is distorted by neighbor Zeeman states. For example, with $I(\nu_1) = I(\nu_2)$, at $B = 1.5$ G, $I$ can go as high as 400 mW/cm$^2$, but at $B = 0.05$ G, $I = 0.5$ mW/cm$^2$ has considerably distorted the shape of the CPT signal. We emphasize that when two laser intensities do not change simultaneously, this square root relation is not followed.

We also considered possible effects of the $4P_{1/2}$ $F = 1$ state, which is split by 30 MHz or $\approx 5$ $\Gamma$ from $F = 2$, on the coherence. Such effects were considered in [17]. If we artificially remove from our calculation the $F = 1$ state, the predicted

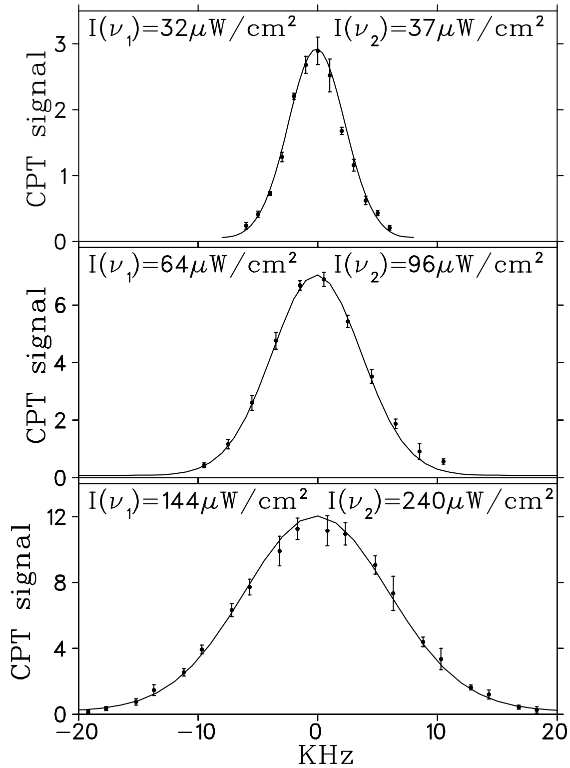


Fig. 5. Experimental condition: $B = 1.51$ G; laser frequencies satisfy $h(\nu_1 - \nu_2) = \Delta E_0$. The calculated curve is not the fitting of measured data, but an independent calculated result from our theoretical model. In the calculation laser intensities were fit from experimental data, other parameters were experimental ones, and the maximum of the calculated curve was normalized to experiment.

width of the coherence does not change. (The amplitude of the fluorescence signal does become smaller, as simply expected because that state is no longer excited.)

A practical aspect, and a main motivation for us, is that the CPT effect would spoil the high nuclear vector polarization from optical pumping desired for nuclear beta decay experiments [18,19]. This is a problem for many atomic experiments, and Berkeland and Boshier [20] have discussed different ways to prevent CPT states. It is clear from our results that the CPT states produced in our system are very fragile. With less than 1 mW/cm$^2$ laser intensity for optical pumping in our system, a 0.1 MHz detuning of $h(\nu_1 - \nu_2)$ from $\Delta E_{M_F}$ is enough to avoid CPT. We also observed that the coherence was spoiled when the laser beam was retroreflected; this is unsurprising in our system because the large Doppler shifts in our relatively hot (600 μK) allow real absorption of light off the Raman resonance from the opposing beams and leave a very small percentage for velocity-selective CPT [1].

## 5. Conclusion

In conclusion, we have used cold atoms prepared by a MOT to study coherent population trapping, and have made corresponding theoretical calculations. The trapped cold atoms allow study of the whole CPT preparation process. Our experiment and calculation agree that the CPT spectral linewidth is approximately proportional to the square root of the laser intensity, and the limits of this relation were explored theoretically.

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