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Ionization spectroscopy in cold rubidium atoms

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We demonstrate photoionization spectroscopy in cold rubidium atoms trapped in a working magneto-optical trap. Three-photon ionization with two-photon resonance proceeds along various channels, with the step-by-step $5S–5P–5D$ transition and with the two-photon excitation of the $5D$ or $7S$ state. The processes are monitored by measuring ion signals which allow sensitive spectroscopy of weak transitions in a cold-atom sample.

Keywords: cold atoms, photoionization.

1. Introduction

In a magneto-optical trap (MOT), atoms are illuminated by intense near-resonant trapping and repumping laser beams that efficiently excite the trapped atoms. For experiments with trapping ^{87}Rb atoms on the D2 line (780 nm), the relevant excited state is the $F' = 3$ hyperfine component of the $5^2P_{3/2}$ state. By simultaneous illumination of Rb atoms with additional light beam of 776 nm, it is possible to excite the higher-lying $5D$ states. Similarly, by using a laser beam at around 760 nm, it is possible to excite the $7S$ state via two-photon absorption from the ground $5S$ state. Energies of the $5D$ and $7S$ states are high enough that atoms excited to these states can be then ionized by one photon at any of the mentioned wavelengths. Thus, by performing resonant excitation of the $5D$ or $7S$ states, one can photoionize the trapped rubidium atoms in the three-photon ionization scheme, which is two-photon resonant. The ionization signals constitute an interesting alternative to the standard optical detection, *i.e.*, absorption and fluorescence signals [1–3].

In this article we present results of three experiments with ionization spectroscopy of ~10^7 ^{87}Rb atoms at the temperature of ~100 μK trapped in a MOT and discuss the potential of this technique for the sensitive measurements of relatively weak transitions.

The cooling/trapping and repumping MOT beams are generated by the external-cavity diode lasers and the 776 or 760 nm light by the CW single-mode titanium

sapphire (TiS) laser. Ions are detected by a channeltron mounted inside the MOT vacuum chamber together with suitable electrodes for attracting ions created in the trap center. Channeltron voltage signal, proportional to the number of ion counts per unit time, is recorded as a function of the TiS laser detuning in order to obtain the ionization spectra.

Such spectra were averaged over 4 traces. The rate of the TiS laser scan was of the order of 1 GHz/s and had no influence on the signal shapes.

2. Ionization spectra

The ionization channels relevant for the described experiments are depicted in Fig. 1 where each diagram shows a different way of excitation of the $5D_{3/2}$ ($7S_{1/2}$) states from the $5S_{1/2}$ ground state. The last step of the ionization, *i.e.*, excitation from $5D$ ($7S$) to continuum, is not shown.

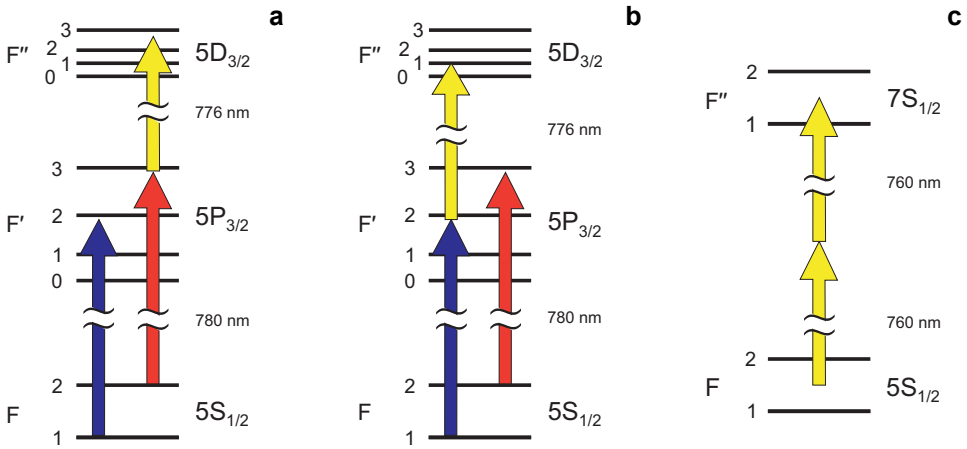

Fig. 1. Transitions with atoms excited to intermediate levels by: step-by-step [$5S(F=2)$–$5P(F'=3)$–$5D$ ($F''=2, 3$)] and two-photon transitions driven by the cooling and TiS lasers (**a**), step-by-step [$5S(F=1)$–$5P(F'=1, 2)$–$5D(F''=0, 1, 2, 3)$] and two-photon transitions driven by the repumping and TiS lasers (**b**), and two-photon transition [$5S(F=2)$–$7S(F''=2)$] driven by the TiS laser (**c**). Arrows depict transitions induced by different lasers: repumping (blue), cooling (red), TiS (yellow). Atoms in the $5D$ or $7S$ states are ionized by absorbing an extra photon from any of the beams.

The choice of specific excitation channel determines the character of the resulting ionization spectra. In the following sections, the spectra characteristic for the three cases presented in Fig. 1 are shown and discussed.

2.1. Spectra with the participation of cooling beams

Figure 2 depicts the typical ionization spectra obtained according to Fig. 1**a**, *i.e.*, with the transitions involving the cooling and TiS beams. Such resonant excitations require

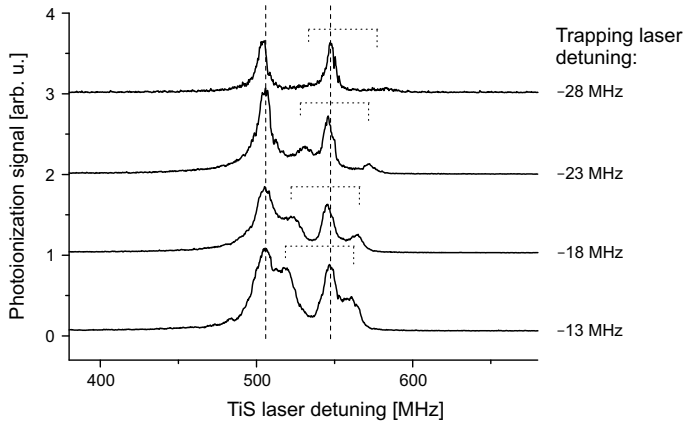

Fig. 2. Typical ionization spectra obtained with the cooling and TiS laser beams. Two components which occur at constant frequencies of the TiS laser represent the step-by-step transitions, whereas those two which are displaced when the cooling laser frequency is varied are associated with the two photon excitation channels of the $F'' = 2$ and 3 hyperfine components of the $5D_{3/2}$ state. The large splitting reflects the hyperfine splitting of the $F'' = 2$ and 3 levels, the varying small splitting depends on the detuning of the cooling beam from the $(F = 2)–(F' = 3)$ transition.

modest laser intensities, and thus were recorded with an uncollimated TiS beam. Each spectrum is recorded as a function of the TiS laser detuning and consists of four components, in spite of the fact that only two transitions are allowed from $F' = 3$ to $F'' = 2$ and 3. Two principal components of the spectrum appear not to be affected by the detuning of the MOT cooling laser. Their separation agrees with the hyperfine structure splitting of the $F'' = 2$ and 3 levels equal to 44.2 MHz [4]. The two extra lines are attributed to the two-photon transitions. These two kinds of transitions have very different dependence on the detuning of the laser exciting the lower transition [5]. By changing the detuning of the cooling laser, it is thus possible to distinguish the step-by-step and two-photon transitions. The latter change their positions for various detunings, while the first ones occur for the fixed TiS laser frequency. Although the range of the available detunings of the cooling laser is limited by the trap stability, still it was sufficient to demonstrate different nature of the two kinds of transitions and allow interpretation of the spectra depicted in Fig. 2.

2.2. Spectra with the participation of the repumping beam

In contrast to the limited detuning of the cooling laser, for sufficiently high repumping laser intensities, it was possible to vary its detuning in a few hundred MHz range with a small effect on the MOT operation. This allowed us to perform a detailed study of the scheme presented in Fig. 1**b**. The ionization spectra recorded in this configuration for different repumper detunings are shown in Fig. 3. Similarly as in Fig. 2, one can recognize the group of transitions that are independent of the repumping-laser frequency and the group which follows the detuning of the repumping light. All

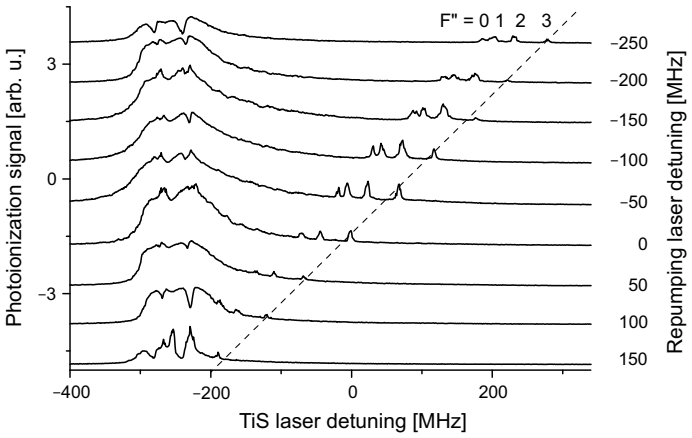

Fig. 3. Ionization spectra obtained with the repumping and TiS lasers for different detunings of the repumping laser relative to the exact resonance with the transition ($F = 1$)−($F' = 2$). The skew line illustrates linear dependence of the two-photon transitions on the repumper detuning, and the structure to the left, which does not move with the repumper detuning, is associated with the cooling laser and atoms excited to the $F' = 3$ state.

resonances that belong to the second groups follow the linear dependence shown by a skew line and are due to two-photon transitions. The group of two-photon transitions has a distinct four-peak structure which results from transitions to all hyperfine sublevels of the $5D_{3/2}$ state. The relative amplitudes of individual peaks are governed by the $F' = 1$ and $F' = 2$ populations which, in turn, depend on the repumping laser frequency.

The wide structure which does not move with the detuning of the repumping laser is due to the interaction with the MOT cooling beams. Atoms are firstly excited by the cooling laser and then by the TiS laser, similarly to the scheme presented in Section 2.1. However, as the TiS laser intensities are much higher here than in the case described in Section 2.1, the signal due to the cooling beams is heavily distorted since the channeltron is easily saturated. Moreover, for large repumping-laser detunings, there is an overall drop of number of atoms remaining in a MOT which also affects the signal amplitudes.

2.3. Two-photon 5*S*−7*S* transition

Another ionization channel studied in the experiment was the two-photon $5S-7S$ transition (Fig. 1**c**). With a resonance linewidth of ~900 kHz [6] this line may be used for laser stabilization. Moreover, the $S-S$ transition is intrinsically immune to the magnetic field in the first order (no Zeeman shift of the lines) [7] which makes it a good frequency standard in laboratory environment. Excitation of this transition, however, requires much higher light intensities, as the probability of this transition is

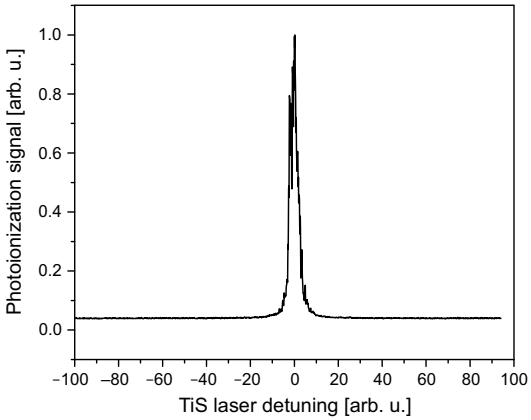

Fig. 4. The ionization signal arising from the two-photon $5S-7S$ transition as a function of the frequency of the TiS laser. The resonance linewidth is dominated by the laser linewidth (~5 MHz), whereas natural linewidth is much smaller (<1 MHz).

around 100 times lower than of the $5S-5D$ transition. This is due to 10 times larger detuning for the two-photon resonance condition (760 nm) from the intermediate $5P$ state.

In the described experiment, we used a TiS laser beam at 760 nm with a few tens of mW, tightly focused to ~13 μm-wide spot. One example of the obtained spectrum is shown in Fig. 4. Within the tuning range of our laser only one of the two hyperfine transitions, $(F = 1)-(F'' = 1)$ and $(F = 2)-(F'' = 2)$, allowed by the $\Delta F = 0$ selection rules [5], is depicted. The spectrum in Fig. 4 is broadened by the 5 MHz linewidth of the available TiS laser. This is a preliminary result aiming at adjusting the detection sensitivity and necessary laser power, so it is missing proper frequency calibration. However, with no averaging and no phase-sensitive detection used, the signal has high signal-to-noise ratio, and thus illustrates the potential of using ionization spectroscopy for studying weak lines in a cold-atom sample.

3. Conclusions

We have performed photoionization spectroscopy of cold ^{87}Rb atoms trapped in an operating MOT. The good signal-to-noise ratio and high sensitivity prove that photoionization spectroscopy is a convenient tool and an interesting alternative to the standard optical spectroscopy, such as the absorption or fluorescence techniques. It is particularly well suited for the studies of weak transitions.

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