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Probing ^{85}Rb MOT in $5P_{3/2}(F=4) \rightarrow 5D_{5/2}(F')$ transitions. In search for effective Rabi frequency

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ABSTRACT

The aim of this work was to provide a simple justification and applicability limits for the concept of effective Rabi frequency being related to an average atom–field interaction in MOT. We sampled ^{85}Rb MOT with a weak probe beam tuned across the $5P_{3/2}$ $(F'=4) \rightarrow 5D_{5/2}(F''=3, 4, 5)$ hyperfine transitions, while the $5S_{1/2}$ $(F=3) \rightarrow 5P_{3/2}(F'=4)$ transition was driven by the red-detuned trapping beam. The probe absorption spectra were registered for a number of detunings Δ and intensities P of the trapping beam. The Autler–Townes splitting δ of the clearly dominating $F'=4 \rightarrow F''=5$ line was the subject of analysis. The character of the space-dependent interactions of atoms with MOT fields is of a complex nature, which brings the notion of the effective Rabi frequency for MOT into challenge. However, we argue that for the range of the typical values of P and Δ, it is justified to characterize MOT with an effective Rabi frequency $\Omega_{0\mathrm{eff}}$, by using the intuitive formula $\Omega_{0\mathrm{eff}} = \sqrt{BP}$, where $\sqrt{B}$ is a mean scaling factor experimentally determined, basing on predictions of a straightforward 3-level model. We postulate that our simple procedure, providing both the $\sqrt{B}$ value and the applicability limits of the approach, should be repeated with each new implementation of MOT (*e.g.*, with trap beams realignment), which may change conditions experienced by cold atoms.

1. Introduction

The pump–probe spectra with cold atoms have been of interest since the early nineties when the magneto-optical trap (MOT) produced in a vapor cell [1] started to play a role of a standard spectroscopy tool, providing nearly Doppler-free environment of relatively dense cloud of cold atoms. We begin with a short overview of some experiments in a cascade-scheme [2–8], which is also the kind of scheme used in our experiment. The goal of Refs. [2–5] was to examine suitability of MOT environment for precise *hfs* spectroscopy aiming at new frequency standards, and/or to provide diagnostic information about the conditions of the trapped atoms. The trapping–cooling D2 transition in alkali metal MOT served as the first step transition. The trapping beam produced the Autler–Townes (A–T) splitting in the spectrum of a weak probe-beam absorption in the second step transition to S or D state of alkali atoms: Cs(8S, 6D) [5], Cs(9S) [2,3], ^{87}Rb(4D) [2] and ^{85}Rb(4D) [4]. More recently, probing by excitation to high Rydberg states (with $n \geq 40$) was reported [6,7]. The pump–probe cascade scheme S–P–D was used for high resolution spectroscopy to determine *fs* and *hfs* for the $7D_J$ states of francium, the short-lived radioactive alkali, trapped in MOT [8]. The authors applied the A–T splitting for the frequency scaling. The experiments were performed either on working MOT, or on optical molasses.

In the present paper we report an experiment in which the ^{85}Rb cascade scheme $5S_{1/2}(F=3) \rightarrow 5P_{3/2}(F'=4) \rightarrow 5D_{5/2}(F'')$ (Fig. 1) was studied with atoms in an operating MOT. The obtained probe absorption spectra are discussed in order to characterize the probed volume with a parameter of effective Rabi frequency, in the easiest possible way. ^{85}Rb-MOT is used in many, if not in most, experiments with cold Rb atoms. Therefore, we have attempted to explore this pump–probe scheme in some details. A practical merit of using the $5P_{3/2} \rightarrow 5D_J$ transition for probing Rb MOT (rather than, *e.g.*, the $5P_{3/2} \rightarrow 4D_J$ transition at 1.5 μm) is its wavelength 776 nm, close to that of the first step Rb-D2 line at 780 nm. Some of the laser diodes nominally at 780 nm, available on the shelves of a Rb-MOT laboratory, can be easily tuned to 776 nm in an ECDL cavity equipped with optics for 780 nm.

Before we go to details of our experiment we briefly recollect the conditions prevailing in MOT and evoke an example from the literature [3], how their complexity can be handled. However, it is expedient to admit here that the cascade scheme is not the only scheme used for probing MOT. Detailed investigations of subtle effects in MOT environment also discussing the problem of MOT inhomogeneities and averaging issues were reported in Ref. [9]. In this work probing at the frequency close to that of the trapping beam was used. Ref. [9] also contains several references to other relevant papers.

Physical conditions, which an individual atom experiences in MOT, vary with atom's position in space. The most obvious is the space-

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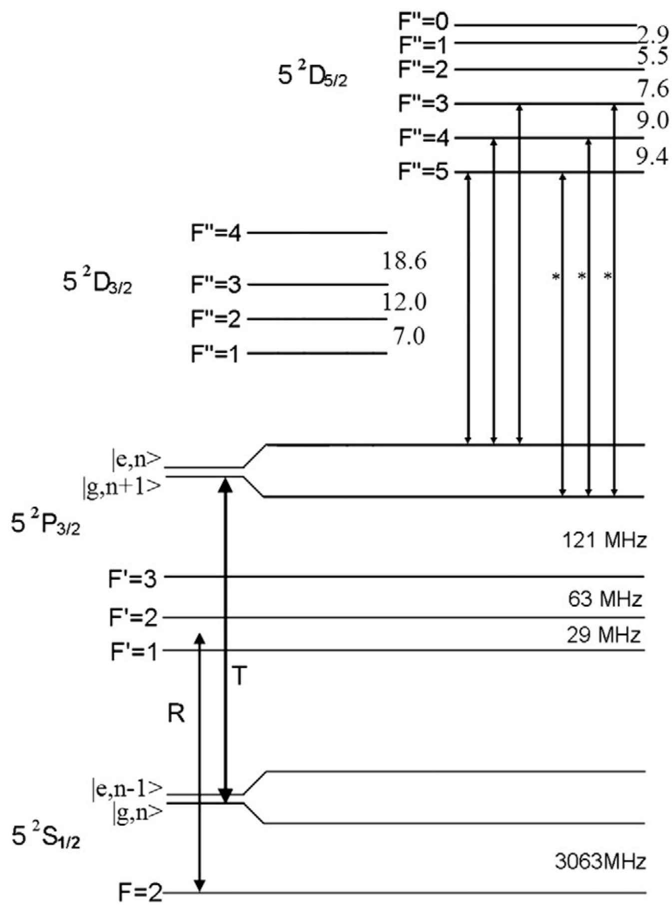

Fig. 1. [85]Rb atomic levels of interest. The positions of the $5S_{1/2}(F=4)$ and $5P_{3/2}(F'=4)$ levels are not marked. Instead, two pairs of states in dressed-state picture (g corresponds to $F=3$ and e to $F'=4$) are symbolically incorporated to justify the Autler–Townes splitting of the three allowed transitions $5P_{3/2}(F'=4)\rightarrow 5D_J$ ($F''=5$, 4, 3). The *hfs* distances (in MHz) for the $5D_J$ states are taken from Ref. [10]. The asterisks mark the "coherent" transitions in the dressed-atom picture, as explained in Section 4. The T and R arrows symbolize the trapping–cooling transition and the repumping transition, respectively.

dependent detuning due to the MOT magnetic field. The distance of laser photon energy from resonance with Zeeman-shifted level varies in space due to the magnetic field strength gradient dictated by the anti-Helmholtz configuration of the MOT coils. The electric field **E** varies macroscopically across the laser beam, regularly, or even irregularly for some diode lasers. The **E** field due to six crossing laser beams exhibits also microscopic variations at the scale of laser wavelength, because of spatial pattern of the beam interference [11]. This picture can be supplemented with further details, *e.g.*, with MOT beams misaligned and/or imbalanced in power, the MOT center may be displaced from the zero-position of the magnetic-field and MOT may even lose its semi-spherical symmetry ([12] and [3] pp. 1391, 1392). For MOT atoms thus experiencing a higher magnetic field, and therefore larger Zeeman shifts of m levels, the effective detuning from the $F=3$-$F'=4$ resonance decreases.

The nature of three-dimensional **E** field intensity distribution, being the result of interference under conditions of the fluctuating relative phase of each of the six MOT beams, as well as variations of the magnetic field over the trapping volume, was discussed among others by Marquardt et al. [3]. The authors describe the model in which they account for spatial MOT inhomogeneities. The model was developed to reconstruct the shapes of resonances in the probe absorption in a two photon 6S–6P–9S experiment in Cs-MOT. As a starting point, a 5-level approximation is considered for each atom interacting with local fields specific to atom's position in the cold cloud. The weighted contributions to the probe absorption line shape are accounted for by numerical integration. The authors argue that considering the whole ensemble of atoms, the contribution to the total line shape of each-atom Rabi-frequency changes as a function of detuning. "This makes it impossible – they conclude – to choose a single value of the electric field to model the splitting dependence on detuning" ([3], p. 1389). The cited sentence suggests that it is, in general, not possible to define the effective Rabi frequency as a physical quantity depending on the average laser power but not on detuning.

Nevertheless in Sec. 5 of Ref. [3] the authors attribute a single value of Rabi frequency of *ca* 15.5 MHz, as the best fitted, to all three spectra presented in Fig. 7 of Ref. [3], by assuming a single Rabi frequency in their model (*i.e.* in the reduced version of the model). The spectra were registered with three different values of detuning Δ from the first-step transition resonance: $\Delta=-7$, -10 and -13 MHz. It should be noticed that these values lie in the range of typical detunings of the trapping beam in Cs-MOT. As it can be inferred from the context, the spectra were taken with the same trapping laser power. One of the experimental spectra, the one with $\Delta=-10$ MHz in Fig. 7 (b) of Ref. [3], was compared both with the theoretical spectrum being the result of authors' full model, and with the result of that model reduced to a single Rabi frequency version. With the full model the broadened widths of the two Autler–Townes peaks are much better reproduced than with the single Rabi frequency model. One can yet observe that both models provide very similar peak distance δ which well reproduces the experimental one. By measuring the peak distances in the experimental spectra in Fig. 7 of Ref. [3] we observed that, for all three Δ, a relation holds

$$\delta=\sqrt{\Omega_{0\mathrm{eff}}^2+\Delta^2}, \tag{1}$$

with approximately the same $\Omega_{0\mathrm{eff}}$ values. These values also reproduce, within a few percent difference, the above mentioned value of 15.5 MHz, the result of the reduced version of the model. Relation (1) has the form of the formula defining generalized Rabi frequency Ω, $\Omega=\sqrt{\Omega_0^2+\Delta^2}$ providing we identify δ with Ω, and $\Omega_{0\mathrm{eff}}$ with Ω_0.

To summarize, we point out to two observations from Ref. [3] of interest for our search of a prescription for effective Rabi frequency. (*i*) Though the MOT atoms meet space-dependent conditions, their inhomogeneity seems to influence more the width of the A–T features in probe absorption than the A–T peak distance. (*ii*) We found that from the A–T peak distances in spectra of Fig. 7 [3] it was possible to make a simple estimate of the effective Rabi frequency value well coinciding with the one obtained *via* a more complicated theoretical approach of Ref. [3]. However, one should note that the use of a simple formula (1) which is related to a two-level atom model, although appeared to be successful, does not have to be *a priori* applicable for a cascade probing.

We use hints from (*i*) and (*ii*) in further considerations.

In our work we were aimed at demonstrating that despite the fact that the atoms in the cold cloud experience complex space-dependent interactions with MOT fields, under some controlled conditions their interactions with the trapping beams can be approximately described as an average interaction related to their ensemble, in the framework of a simple, straightforward theoretical approach.

2. Model

In the present work, we registered a series of pump–probe spectra in a broad range of detunings and powers of the trapping laser. The parameter range was spanned to the limits of possibly stable MOT operation. By assuming that the complexity of conditions in MOT is more imprinted in the width (broadening) of A–T resonances in probe