SPATIAL CONTROL OF Na EXCITATION BY MEANS OF INTERFERENCE DUE TO AUTLER-TOWNES EFFECT

N. Bezuglov[1], A. Ekers[2], K. Miculis[2], I. Sydoryk[2], C. Andreeva[2,3], B. Mahrov[2], E. Saks[2], I. Ryabtsev[4], R. Garcia-Fernandez[5], K. Bergmann[5]

[1]*V. Fock Institute of Physics, St. Petersburg State University, 198904 St. Petersburg, Russia*
[2]*Laser Centre, Faculty of Physics and Mathematics, University of Latvia, LV-1002 Riga, Latvia*
[3]*Institute of Electronics, Bulgarian Academy of Sciences, Sofia 1784, Bulgaria*
[4]*Institute of Semiconductor Physics, Department of Quantum Electronics, 630090 Novosibirsk, Russia*
[5]*University of Kaiserslautern, Department of Physics, D-67653 Kaiserslautern, Germany*

We present the results of detailed calculations, which show that spatial distribution of atomic excitation can be controlled in a three-level scheme by creating Ramsey interference employing the Autler-Townes effect. The first excitation step is realized by strong and tightly focused pump field creating spatially-varying dressed states. The second excitation step can take place at two spatial locations (Landau-Zener points), where the second laser field is resonant with one of the dressed states. Thus, two alternative excitation pathways to the final level exist, whose constructive or destructive interference determines the transition probability at the second Landau-Zener region. In this way, the spatial distribution of populations of excited states can be controlled by varying the laser frequencies and intensities. Moreover, moderate detunings of the pump field are favorable for the observation of interference effects. The experimental realization of the idea is in progress.

Introduction

The method of separated oscillatory fields (Ramsey spectroscopy) [1] has for a long time become a basic tool in high-precision experiments. The basic concept is that electromagnetic field is applied to the sample initially for a short time, its amplitude is then reduced to zero for a relatively long period, after which it is increased again for a short time, with phase coherence being preserved between the fields. Varying the frequency of the field, narrow interference fringes in the spectrum are observed. Due to its numerous advantages, the technique has been extended from the RF also to the optical frequency domain [2].

Application of this technique to atoms dressed in a strong laser field has been reported in [3], where interference fringes in the Autler-Townes spectra [4] have been observed. In that study, a closed three-level system was coupled by a resonant pulsed pump laser field in the first excitation step. The strong pump field creates time-varying dressed states, which were probed by a simultaneous probe pulse in the second excitation step. Thus, very fast switching of the second-stage excitation can be realized, best contrast being obtained when the pulse duration is close to the transform limit. Besides this technical difficulty, this scheme does not allow the precise spatial control of the excitation positions.

In this communication we propose a different excitation scheme, using cw lasers for the atomic excitation. The results of our detailed calculations show that in this way it is possible to realize control of the spatial distribution of the atomic excitation.

Description of the method

The schematic realization of the proposed experiment is presented in Fig.1. A supersonic sodium beam is crossed by two cw laser beams, which couple an open three-level ladder system (Fig1a). The lasers are focused in such a way that a strong and short (tightly focused) pump laser field S couples the two lower levels $|g\rangle$ and $|e\rangle$, and weak and long (less tightly focused) probe laser field P couples the intermediate level $|e\rangle$ and the upper level $|f\rangle$. Because of the tight focusing, the pump laser thus creates two spatially varying dressed states correlating to $|g,n+1\rangle$ and $|e,n\rangle$ states (see Fig. 1b), n being the photon number per laser field

mode. It should be noted that the time dependence is determined by the time of flight of the atoms through the laser beam with spatially varying intensity. The energy difference between both dressed states is determined by the pump field Rabi frequency Ω_R and the detuning of the pump field from resonance Δ_S, as seen in Fig.1b. When the frequencies of both laser fields are fixed, the excitation of the upper level can take place at two distinct spatial locations (Landau-Zener transition points x_1 and x_2 in Fig.1b), where the second laser field is resonant with one of the dressed states created via interaction of the system with the pump laser field. This leads to two alternative excitation pathways of the level $|f\rangle$, whereby the probability amplitude of this level at the second Landau-Zener transition region is determined by the constructive or destructive interference of both excitation pathways.

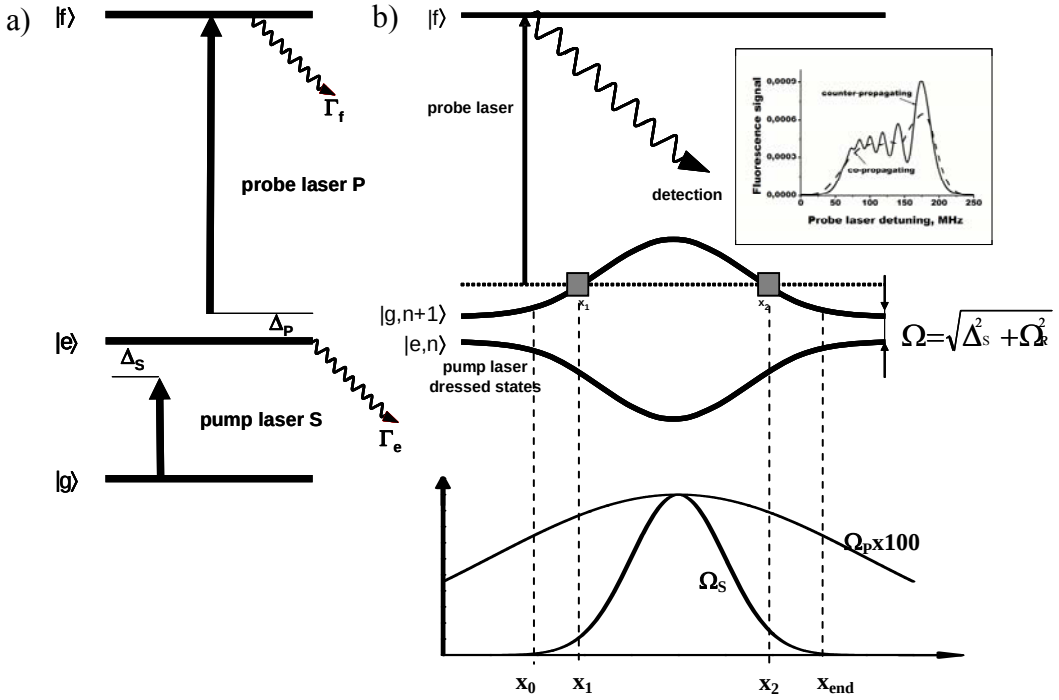

Fig.1. Interaction scheme.

The phase difference between the two excitation pathways can be controlled either by varying the pump laser intensity at fixed laser frequencies, or by scanning the probe laser frequency at fixed laser intensities.

Results and discussion

In order to test the proposed methodology, a simple theoretical model has been developed. The probability amplitudes of a three-level atomic system subjected to two laser fields are calculated. The levels decay is not included, but the model gives good qualitative results, since the time of flight of the Na atoms through the interaction region is short compared with the lifetimes of the excited states. This is considered by introducing a short Gaussian time-dependent pump field. The resulting population of the $|f\rangle$ level is averaged over the interaction time and reveals a number of interference fringes within the interval between the Autler-Towns doublet.

In a real experiment, though, these fringes are washed to some extent due to several factors. The main ones are the real hyperfine structure of Na atom, the velocity distribution of the atoms along the beam propagation direction (with a width of 260 m/s in our case), and the residual Doppler broadening. The latter factor is minimized by using counter-propagating pump and probe laser fields. In our experimental arrangement, the residual Doppler

broadening equals about 20 MHz. The atomic population distribution among Zeeman sublevels can be favourably manipulated by means of using circularly polarized light and choosing V-type of optical transitions. Then, the realization of preliminary atomic orientation using a part of the pump beam will lead to Zeeman optical pumping onto the Zeeman sublevel with highest $|m_F|$. In this case, the transverse magnetic field should be carefully compensated.

The most straightforward choice of transitions is: $3S_{1/2}$ (F = 2) → $3P_{3/2}$ (F = 3) → $4D_{5/2}$ (F = 4). The disadvantage here is that the hyperfine levels of the $4D_{5/2}$ state are closely spaced and will also be partly populated during the probe laser frequency scan. Another option is to use as a final state the $5S_{1/2}$ level. Although the probability of the $3P_{3/2} \rightarrow 5S_{1/2}$ transition is smaller than for the $3P_{3/2} \rightarrow 4D_{5/2}$, the two hyperfine levels of the $5S_{1/2}$ state are more separated, by156 MHz, which would lead to a better contrast of the fringes. In both cases, though, the excitation of the final state is registered via spontaneous relaxation to the $4P_{3/2}$ level, which decays to ground state as a UV transition at 330 nm.

For a more precise description of the atomic system and the experimental conditions, numerical calculations of the density matrix equations of motion are made using the split propagation technique [5]. The theoretical model will be presented in more details elsewhere [6].

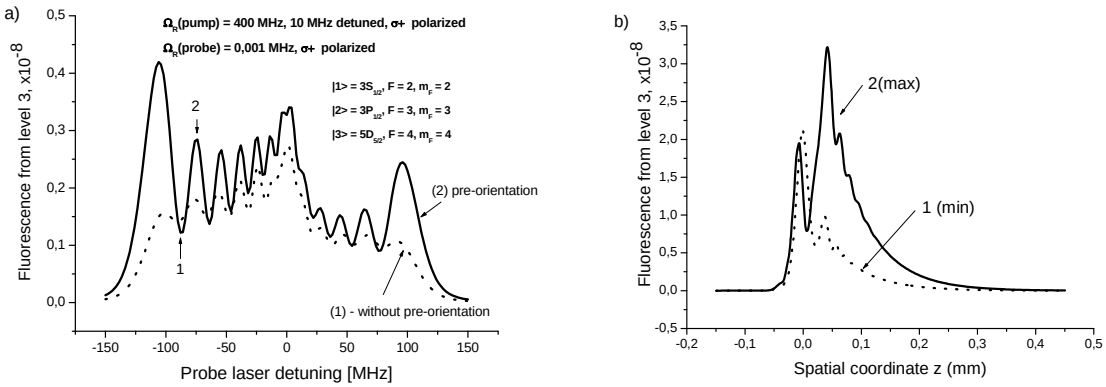

Fig.2. Fluorescence from the final |f⟩ state of Na vs (a) the probe laser field detuning (curve (1) – without pre-orientation of the atomic sample, curve (2) – with realization of orientation), and (b) spatial coordinate z along the atomic beam (curve (1) – dependence of the first minimum, and (2) – of the second maximum). The following parameters have been used: atomic beam flow velocity v(flow) = 1160 m/s, laser beam radii r(pump) = 0,025 mm, r(probe) = 0,08 mm, no residual Doppler broadening included.

Fig.2 illustrates the case when the Na atoms are excited at the $3S_{1/2}$ (F = 2) → $3P_{3/2}$ (F = 3) → $4D_{5/2}$ (F = 4) transitions by means of two σ^+ polarized laser fields. The relevant parameters used in the calculations and listed in the figure caption correspond to the real experimental conditions. As can be seen from Fig.2a, optical pumping of the atomic population onto a single Zeeman sublevel before the interaction region leads to significant increase in the contrast of the fringes (see curve 2) as compared to the case when at the onset of the interaction the atomic population is equally distributed among the ground-state Zeeman sublevels (curve (1)).

An interesting consequence of this interference pattern is the resulting variation of the spatial distribution of the excitation of the atoms to the final state for different detuning of the probe laser field. This variation is illustrated in Fig.2b for a detuning of the weak field set to the first interference minimum (curve 1) and the second interference maximum (curve 2).

Thus, it is possible to realize switching of the population of the final state at the point x_2 by means of changing the intensity of the pump laser or simply tuning the frequency of the probe laser between interference minima and maxima.

A similar experimental arrangement has been used in [7] in relation to lifetime measurements using Autler-Towns spectra. A supersonic molecular Na_2 beam is used. It should be noted, that in this work the interference fringes were not resolved. The experimental realization of the idea is in progress. The modifications, as compared to the earlier experiment, include the use of counter-propagating laser beams to avoid averaging due to Doppler effect in the diverging atomic beam, and more tight focusing of the pump beam to increase the sharpness of the fringes. Moreover, our calculations show that the proper choice of Rabi frequencies is essential for the observation of the interference pattern.

Conclusion

We have shown that in a three-level atomic system coupled by a strong pump laser field in a first excitation step and a weak probe laser field as a second step, it is possible under certain conditions to create Ramsey-type interference in the Autler-Towns spectra. The interference patterns of the excited levels open interesting possibilities for application. It is possible to realize spatial control of the distribution of the atomic excitation with a μm resolution by simply changing the detuning of the probe laser or the intensity of the pump laser. Such a technique for spatial switching of population may find applications, e.g., in the beam lithography techniques [8], especially those exploiting atoms in Rydberg states. The spatial population control can be easily transformed into temporal switching, with a resolution of down to several ns. This makes the technique attractive for applications involving novel quantum logic schemes [9].

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