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Pulsed standing wave deflection of sodium atoms

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Abstract. We study the deflection of sodium atoms by a resonantly tuned pulsed standing wave of high field intensity. The effects of the phase fluctuations of the pulsed laser field on the momentum distribution of the deflected atoms are experimentally determined. The results are explained using a theoretical model based on the generalized density matrix formalism of two-level atoms.

PACS. 32.80.Lg Mechanical effects of light on atoms, molecules, and ions

1 Introduction

Standing wave laser fields have been extensively used to control the motion of neutral atoms [1,2]. For resonantly tuned fields the center-of-mass motion of the atoms is influenced by the redistribution of photons between the two counter-propagating laser beams through absorption and emission processes. In the absence of spontaneous emission the atoms will gain momentum in the directions of the laser beams. This type of deflection has been observed experimentally by several research groups during the past years [3–12]. In most cases, the standing wave has been produced using narrow bandwidth CW lasers. Depending on the experimental parameters the atomic beam can be split in two as in the case of Bragg scattering [8] or the Stern-Gerlach effect [10] or it may be divided into many different diffraction orders through the Kapitza-Dirac effect [4,7]. Because of these effects the standing wave has become a useful tool in the field of atom optics.

In the case of CW lasers, the relatively low intensities available necessarily limit the momentum transfer from the standing wave to the atoms to quite small values. This is particularly true if coherent deflection is required. The use of standing waves is then restricted to deflecting atoms only to small angles, which is often not very practical. Orders of magnitude higher intensities can be generated by using pulsed lasers. Then the rate of momentum transfer to the atoms also becomes significantly larger than in the CW case. As a result, large deflection angles may be produced even with pulses of only a few nanoseconds duration. For such short interaction times the effects of spontaneous emission processes become negligible even for resonantly tuned laser fields. This should then allow pulsed standing waves to be used for the resonant deflection of multilevel atoms, and even molecules. It is typical for pulsed laser sources, however, that the coherence time of the light field is shorter than the interaction time. The coherence of the deflection will thus be influenced by the phase fluctuations of the laser field. In this work we are interested in the effects caused by the limited coherence of the laser field and we measure here the transverse momentum distribution of sodium atoms after deflection from a resonantly tuned pulsed standing wave having a limited coherence time. The measured distribution will be compared with numerical calculations made using the density matrix formalism for two level atoms and, on the other hand, with analytical result for the fully coherent deflection.

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2 Theory

In coherent interaction with a resonantly tuned standing wave the rate of momentum transfer to the center-of-mass of a two-level atom is proportional to the Rabi flipping frequency $\Omega = \mu_{\text{eg}}\mathcal{E}(\mathbf{R})/\hbar$, where μ_{eg} is the dipole matrix element for the transition and $\mathcal{E}(\mathbf{R})$ is the electric field amplitude at the center-of-mass coordinate $\mathbf{R}$. The coherence of the deflection process will thus depend on the ratio of the Rabi period to the coherence time τ of the laser field and to the interaction time T. If the coherence time of the laser field is much shorter than the Rabi period, *i.e.* $\tau \ll \Omega^{-1}$, the deflection process will be diffusive and the momentum distribution will have a Gaussian shape [13,14]. In the other extreme, $\tau = \infty$, the deflection will be fully coherent. The resulting momentum distribution can then be described as due to the Kapitza-Dirac process, the Stern-Gerlach effect or the Bragg scattering depending on the experimental conditions [15–20]. For pulsed lasers, the coherence time will typically be in between the above regimes and the deflection profile will include both a diffractive and a diffusive component. We will consider here a laser pulse with $\Omega > \tau^{-1} > T^{-1}$.

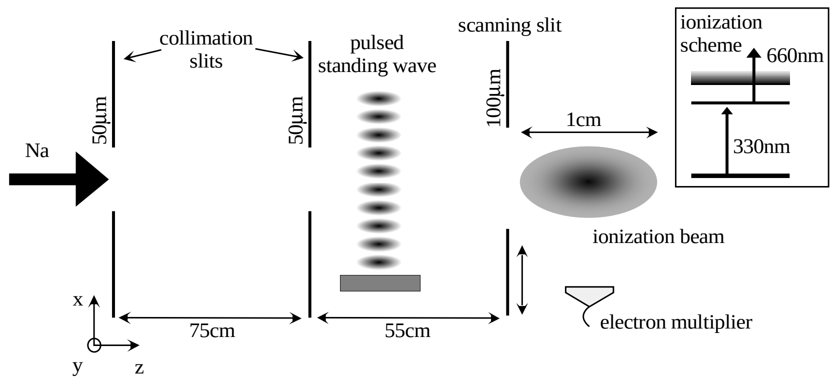

Fig. 1. Experimental setup for measuring the deflection of a sodium beam by a pulsed standing wave.

At intermediate coherence times the momentum distribution of the deflected atoms can be determined by solving the generalized density matrix equations with a relaxation term included in the nondiagonal elements. Since the general equations are rather complicated, some simplifying assumptions are needed to solve for the final momentum distribution. Firstly, the standing-wave geometry allows the Raman-Nath assumption which neglects the atomic motion parallel to the laser beams during the interaction time. Secondly, we assume the temporal pulse profile to be square shaped with duration T. The probability for the atom to end up in a final momentum state $p = n\hbar k$ can then be calculated by numerically integrating the equation [21]

$$P_n(T) = \frac{1}{\lambda^2} \int_{-\lambda/2}^{\lambda/2} \int_{-\lambda/2}^{\lambda/2} \mathrm{d}u \mathrm{d}x I(x,u,T) \mathrm{e}^{-inku}, \qquad (1)$$

where $\lambda = 2\pi/k$ is the wavelength of the laser field, and

$$I(x,u,T) = \mathrm{e}^{-\frac{T}{2\tau}} \left(\cos(\omega_1 T) + \frac{1}{2\omega_1 \tau} \sin(\omega_1 T) \right). \qquad (2)$$

Here $\omega_1 = [(\Omega \sin(kx) \sin(ku/2))^2 - (1/2\tau)^2]^{1/2}$. In the limit $\tau = \infty$ the impulse response I reduces to that of coherent deflection and equation (1) gives the familiar Bessel type diffraction pattern. At intermediate relaxation rates the number of atoms deflected to low momentum states will increase. The envelope of the momentum distribution will in this case resemble a double peaked Bessel distribution with an extra peak around the zero momentum [21]. As the relaxation rate is further increased the central peak will start to dominate and the momentum distribution will take a diffusive shape. In the limit of fast relaxation the deflected momentum distribution can be calculated using the random walk model [14]. Assuming a broadband laser field with $\tau \ll \Omega^{-1} \ll T$ the resulting momentum distribution can be described by a Gaussian distribution with a width of $\Omega(T\tau)^{1/2}$.

3 Experiment

The experimental setup for measuring the final momentum distribution of the deflected atoms is shown schematically in Figure 1. The atomic beam was produced using a thermal source of sodium atoms at a temperature of about 350 °C. The beam was collimated by using two narrow slits with dimensions 50 μm ×1 cm positioned 75 cm apart. A slit parallelism of better than 1 mrad was measured using optical diffraction techniques. The resulting divergence of the atomic beam in the x-direction was about 0.1 mrad. The divergence is not a problem since it is small compared with the spread of the deflected atom distribution. The deflecting standing wave was produced by retro-reflecting from a flat dielectric mirror a collimated laser beam. The laser source was a pulsed Nd:YAG laser pumped dye laser (Quantel YG580 and TDL50). The parallelism between the mirror surface and the atomic beam was measured to be within 1 mrad. The laser beam used to produce the standing wave had an elongated spatial profile with approximately a Gaussian intensity profile in the z-direction and a constant intensity across the atomic beam in the y-direction. The width of the laser beam in the z-direction was 0.5 cm and 2 cm in the y-direction. The smoothness of the intensity distribution across the laser beam was improved by spatial filtering. The transverse motion of the atoms inside the standing wave is well within the limits of the Raman-Nath assumption made in the derivation of equations (1, 2).

The atomic beam profile after the deflection was measured using a 100 μm×1 cm scanning slit together with an ion-detector. The slit was positioned 53 cm downstream from the interaction region. After the slit the sodium atoms were ionized in a two-step resonance ionization configuration (see for example Ref. [22]) using an excimer laser pumped pulsed dye laser (Lambda Physik EMG 103 and FL2002) with a pulse duration of about 10 ns as the radiation source. The triggering of the excimer laser was delayed to allow the deflected atoms in a chosen longitudinal velocity group to reach the detection zone after interaction with the standing wave. The dye laser was tuned such that its second harmonic output frequency generated in a KDP crystal was in resonance with the 3S–4P transition (330.234 nm) of sodium. The atoms excited to the 4P level were then ionized by the fundamental-frequency laser beam (660.468 nm), remaining after the second harmonic generation (Fig. 1). The intensities of these laser fields were chosen such that the two-step transition was fully saturated. The sodium ions were then accelerated to 2500 eV and detected with an electron multiplier (Hamamatsu R515). An advantage of this detection method

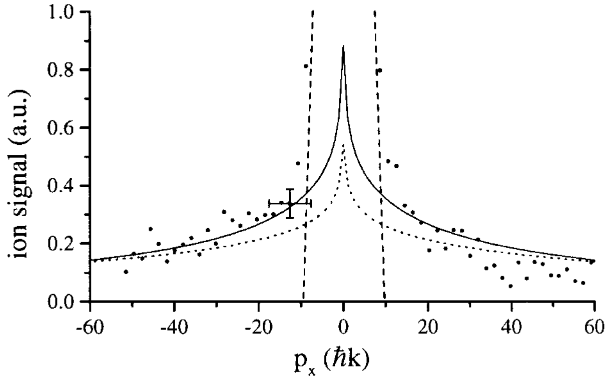

Fig. 2. Momentum distribution of sodium atoms deflected from a pulsed standing wave. The transverse momentum p_x is given in units of $\hbar k$. The experimental data are represented by the dots. The dotted line is a theoretical momentum distribution based on equation (1) calculated using the upper limit value of $\Omega = 1.78 \times 10^{12}$ s^{-1} for the effective Rabi frequency. The solid line represents the theoretical momentum distribution with a factor of two smaller Rabi frequency and shorter coherence time. The experimental error bars are indicated for one data point. The dashed line is the profile of the atomic beam without the deflecting laser pulses.

is the high sensitivity of resonance ionization to only the selected atomic species and the possibility for a good time-of-flight resolution. In our case the velocity resolution in the z-direction was about 20 m s^{-1} determined by the 1 cm width of the ionizing laser beam.

4 Results

In Figure 2 is shown a measured momentum distribution of the sodium atoms after deflection from a resonantly tuned pulsed standing wave with a duration of 9 ns (FWHM). The intensity of the laser beam at the peak of the Gaussian spatial distribution averaged over the temporal pulse profile was $I = 0.6$ MW cm^{-2}. The coherence time of the laser field was measured using interferometry to be 0.1 ns which corresponds to the multimode operation of the pulsed Nd:YAG-laser pumped dye laser. The dots in Figure 2 correspond to the measured transverse position distribution of the atoms which was transformed to a momentum distribution by dividing the measured position values with the time-of-flight (550 μs) of the detected atoms. Since the thermal atomic beam is continuously on, there will always be a large amount of atoms in the detection zone which have not been in the interaction zone at the time of the standing-wave pulse. Therefore, the measured distribution will be dominated at the low momentum values ($|p_x| \leq 10\hbar k$) by these non-deflected background atoms and our measurement will only reveal the higher momentum part of the distribution. The main characteristics of the deflection profile are, however, visible from the data at the high momentum states. The experimental transverse momentum resolution was limited to $10\hbar k$ mainly by the width of the scanning slit, the divergence of the atomic beam and its width at the standing wave position. The effects of the measurement resolution on the observed distribution are small for the high momentum states and were therefore neglected in the comparison of the measurement results with theory.

To allow a comparison between the experimental data and the theory the value for the effective Rabi frequency of the interaction needs to be known. An upper limit for this frequency can be calculated by neglecting the hyperfine structure of the power broadened sodium D_2 line and assuming that all laser modes are resonant with the atomic transition. In this case, the Rabi frequency corresponding to the 0.6 MW cm^{-2} laser intensity is $\Omega = 0.9 \times 10^{12}$ s^{-1} (calculated using the line strength $S = 25.4a_o^2e^2$ for the sodium D_2 line [23]). The corresponding theoretical momentum distribution, including the effects of the Gaussian profile of the laser beam in the z-direction, is shown in Figure 2 by the dotted line. Since the distribution of the deflected atoms could be measured only for the higher momentum states, the vertical scaling of the theoretical momentum distribution could not be directly determined from the area of the deflection profile. Instead, it was adjusted to yield an optimum fit with the measurement points at $|p_x| > 10\hbar k$. We notice that the theoretical momentum distribution (the dotted curve) is spread out more than the experimental distribution. This is as expected, since the momentum distribution is quite sensitive to the value of the Rabi frequency, which for the dotted curve is unrealistically high. If the hyperfine structure of the atomic transition and the mode structure of the laser were taken into account the effective Rabi frequency would reduce from the value calculated above. Also, due to the multimode structure of the deflecting laser beam the exact value for the coherence time τ probably differs from the measured one. The exact inclusion of these factors in the calculation is, however, quite difficult. Here we content ourselves to notice that a reduction of the stated values of the Rabi frequency and the coherence time just by a factor of two already brings about a much better fit between the experimental data and the theory, as is depicted by the solid line in Figure 2.

The stochastic noise in the measured distribution is mainly due to a small amount of background sodium gas in the ionization region (vertical error bar in Fig. 2). To increase the signal-to-noise ratio the longitudinal velocity spread of the atomic beam should be reduced. In our case only about 1% of the atoms deflected by the pulsed standing wave are detected because of the wide velocity spread of the thermal atomic beam. In addition, the data show a slight asymmetry in the momentum distribution which is probably due to a small misalignment effect in the experiment.

The effects of the phase fluctuations of the laser field can be clearly seen by comparing the distributions in Figure 3. The distributions were calculated for a laser beam with a square-shaped intensity profile both in the x and the z-direction using the Rabi frequency reduced by a factor of two from the stated upper limit value, and a coherence time a factor of two shorter than the measured value. In the coherent case a significant part

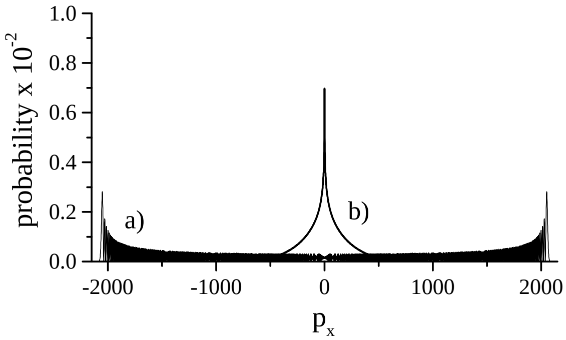

Fig. 3. Calculated momentum distributions at two different coherence times of the laser field. Curve (a) corresponds to the fully coherent case and curve (b) to the value of field coherence in our experiment. The momentum distributions were calculated for a square shaped laser beam profile using the effective Rabi frequency of $\Omega = 460 \times 10^9$ s^{-1}. A value of $\tau = 0.05$ ns that corresponds to the solid curve in Figure 2 was used for the coherence time in (b). The transverse momentum p_x is given in units of $\hbar k$.

of the population is concentrated around the two side maxima of the Bessel function distribution. Of course, for our case, the coherence time of the laser field can in reality be increased only up to the Fourier limit. Then the populations of the side maxima will be somewhat reduced as compared to the fully coherent case but they will still dominate over the low momentum states [21]. In our experimental case the coherence of the deflection is reduced significantly by the phase fluctuations of the laser field. The effect of the reduced coherence on the momentum distribution is already quite dramatic even though the coherence time is still much longer than the Rabi period (see curve (b) in Fig. 3). This suggests that large deflection angles could be achieved even at relatively small laser beam intensities if resonant standing waves with Fourier limited bandwidth are used.

5 Conclusions

The deflection of sodium atoms by a resonantly tuned pulsed standing wave of high field intensity was studied. The aim was to determine the effects of the phase fluctuations of the field on the deflected momentum distribution at intermediate coherence times of the field. The standing wave used in the experimental measurements was produced by a pulsed dye laser with a pulse duration of 9 ns. The intensity of the laser beam was chosen such that the corresponding Rabi period was shorter than the 0.1 ns coherence time of the laser field. At a laser beam intensity of 0.6 MW cm^{-2} the spread of the measured momentum distribution corresponds to transverse velocities of a few m s^{-1}. The shape of the measured momentum distribution was explained using a theoretical model based on the generalized density matrix formalism for two-level atoms. The experimentally observed transverse momentum values were seen to be in a reasonable agreement with the theoretical model. A comparison of the results with the fully coherent case showed that the phase fluctuations of the laser field drastically reduce the achievable transverse momentum values. The results suggest that large deflection angles can be reached if resonantly tuned standing waves with a bandwidth close to the Fourier limit are used. In that case the deflected momentum distribution will resemble the Bessel function distribution of the coherent deflection. The transverse velocities will thus be proportional to the Rabi frequency which for pulsed lasers may be orders of magnitude higher than for CW lasers.

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References

1. A.P. Kazantsev, G.I. Surdutovish, V.P. Yakovlev, *Mechanical Action of Light on Atoms* (World Scientific, Singapore, 1990).
2. *Atom Interferometry*, edited by P. Berman (Academic Press, San Diego, 1997).
3. E. Arimondo, H. Lew, T. Oka, Phys. Rev. Lett. **43**, 753 (1979).
4. P. Moskowitz, P. Gould, S. Atlas, D. Pritchard, Phys. Rev. Lett. **51**, 370 (1983).
5. P. Moskowitz, P. Gould, D. Pritchard, J. Opt. Soc. Am. B **2**, 1784 (1985).
6. V.A. Grinchuk, E.F. Kuzin, M.I. Nagaeva, G.A. Ryabenko, A.P. Kazantsev, G.I. Surdutovich, V.P. Yakovlev, J. Opt. Soc. Am. B **2**, 1805 (1985).
7. P. Gould, G. Ruff, D. Pritchard, Phys. Rev. Lett. **56**, 827 (1986).
8. P. Martin, B. Oldaker, A. Miklich, D. Pritchard, Phys. Rev. Lett. **60**, 515 (1988).
9. P. Gould, P. Martin, G. Ruff, R. Stoner, J.-L. Picquè, D. Pritchard, Phys. Rev. A **43**, 585 (1991).
10. T. Sleator, T. Pfau, V. Balykin, O. Carnal, J. Mlynek, Phys. Rev. Lett. **68**, 1996 (1992).
11. V.A. Grinchuk, E.F. Kuzin, M.I. Nagaeva, G.A. Ryabenko, V.P. Yakovlev, JETP Lett. **57**, 549 (1993).
12. Ch. Kurtsiefer, C. Ekstrom, T. Pfau, S. Spälter, J. Mlynek, Phys. Rev. Lett. **73**, 1223 (1994).
13. S. Stenholm, J. Javanainen, Appl. Phys. **16**, 159 (1978).
14. E. Arimondo, A. Bambini, S. Stenholm, Phys. Rev. A **24**, 898 (1981).
15. R.J. Cook, A.F. Bernhardt, Phys. Rev. A **18**, 2533 (1978).
16. R.J. Cook, Phys. Rev. Lett. **41**, 1788 (1978).
17. R.J. Cook, Phys. Rev. A **22**, 1078 (1980).
18. A.F. Bernhardt, B.W. Shore, Phys. Rev. A **23**, 1290 (1981).
19. C. Tanguy, S. Reynaud, C. Cohen-Tannoudji, J. Phys. B: At. Mol. Phys. **17**, 4623 (1984).
20. M. Marte, S. Stenholm, Appl. Phys. B **54**, 443 (1991).
21. P. Ryytty, M. Kaivola, C.G. Aminoff, Quantum Semiclass. Opt. **10**, 545 (1998).
22. G. Hurst, M. Payne, *Principles and Applications of Resonance Ionization Spectroscopy* (Adam Hilger, Bristol, 1988).
23. W.L. Wiese, M.W. Smith, B.M. Mills, National Stand. Ref. Data Ser. Nat. Bur. Stand. (U.S. Government Printing Office, Washington, 1969), Vol. 22.