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Observation of a transient response of recoil-induced resonance: A method for the measurement of atomic motion in an optical standing wave

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We demonstrate a method to directly observe the dynamics of motion of cold atoms in an optical standing wave using a recoil-induced resonance. By detecting a transient response of this resonance, we observed the interaction between an atomic population grating and a periodic optical potential. Using this method, we investigated the lifetime of the atomic grating under various conditions in the optical potential. As a result, we obtained the appropriate conditions for the long lifetime and observed the narrowest linewidth in the recoil-induced resonance corresponding to the atomic temperature of 4.4±0.3 μK for ^{87}Rb atoms.

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Recent developments of laser cooling and manipulation techniques of atoms have made it possible to investigate the wave nature of atoms in such fields as atomic interferometers [1]. Under the typical condition for the cold atoms in an optical standing-wave potential, where the atomic de Broglie wavelength is comparable to the optical wavelength, we have to consider atoms as atomic waves rather than particles. The interaction between the cold atoms and such a periodic optical potential is essential for the cooling processes of stimulated [2,3] or polarization gradient [4–7] cooling and the quantized motions of atoms in an optical crystal [8–14]. Most of the related experiments have mainly showed the stationary properties of atoms, such as final velocity distribution of cooled atoms and the quantized energy structure of atoms in the optical potential. Besides the stationary properties, the dynamic properties of atomic motion are also important and are inevitable in understanding the cooling process involving the damping force to the atoms in the optical potential [15]. In recent experiments [16–20], the velocity distribution of cold atoms was precisely measured using a recoil-induced resonance. In this paper, we propose a method to measure the dynamic property of atomic motion in a periodic optical potential using the recoil-induced resonance. Detecting the transient response of the recoil-induced resonance, we can observe the damping oscillation that reflects the interaction between the atomic grating and the periodic optical potential. By using this method, we can obtain the lifetime of the atomic grating or the coherence time of atomic momentum states in the periodic optical potential.

In the following part of this paper, we will first show the theoretical interpretation of the transient response of the recoil-induced resonance. Next, we will present the experimental results obtained by this method and will show the experimental approach to study the dynamics of cold atoms. From these experimental results, we obtained the conditions for the long lifetime of the atomic grating. Finally, as an application of the present study of atomic dynamics, we will show the results of the velocity distribution measurement of cold ^{87}Rb atoms using the recoil-induced resonance under these conditions.

We consider the situation where the two probe beams with wave vectors $\vec{k}_1$ and $\vec{k}_2$ cross in a cold atomic vapor at an angle θ. Their angular frequencies ω_1, ω_2 are detuned from the atomic resonant frequency by Δ, and their frequency difference $\delta = \omega_2 - \omega_1$ is much smaller than Δ. Two beams have parallel and linear polarization in the direction perpendicular to the probe beam plane. Initially, frequency difference δ is fixed to zero and then rapidly switched to a nonzero value. The transient response of the recoil-induced resonance can be measured by detecting the transmitted intensity of one of the probe beams. The intensity change of the probe beam is given by the imaginary part of the polarization P induced by two probe beams, and is approximately expressed as

$$\mathrm{Im}\{P\} \cong -\frac{2\mu\chi}{\Delta}\int dr_q \sin(qr_q - \delta t)\,\psi^*(r_q,t)\,\psi(r_q,t). \tag{1}$$

Here, χ, μ, $\psi(r_q,t)$, and r_q are the Rabi frequency, the transition dipole moment, the atomic wave function of the motion of the center of mass, and the projection of radius vector on $\vec{q}$, where $\vec{q} = \vec{k}_2 - \vec{k}_1$ and $q = |\vec{q}|$. It is a modified equation that describes the signal of the recoil-induced resonance in terms of the coherence between the momentum states [20]. From Eq. (1), one can easily observe that the signal is contributed only from the component of atomic density modulated by $\sin(qr_q - \delta t)$. The motion of the atomic center of mass is governed by the Hamiltonian that includes the potential with the periodicity of $\cos(qr_q - \delta t)$. Therefore, initially, atomic population grating modulated by $\cos(qr_q - \delta t)$ is generated with δ fixed to zero. After rapidly switching δ to a nonzero value, periodic interaction between the atomic grating and the optical standing wave moving with the speed of δ/q is induced. As it can be understood by Eq. (1), this periodic interaction manifests itself as an oscillation of the probe signal with frequency δ. The time evolu-

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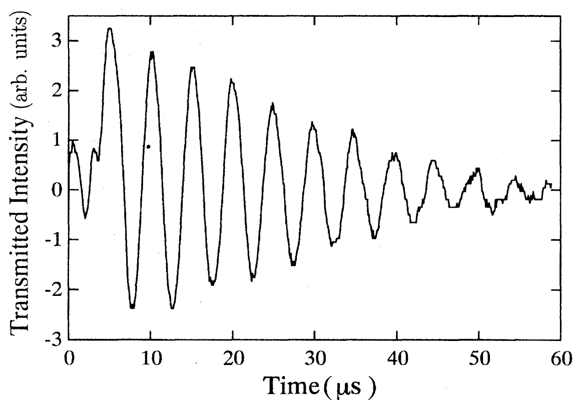

FIG. 1. Transient signal of recoil-induced resonance. At 0 μs, the frequency difference was switched to a nonzero value.

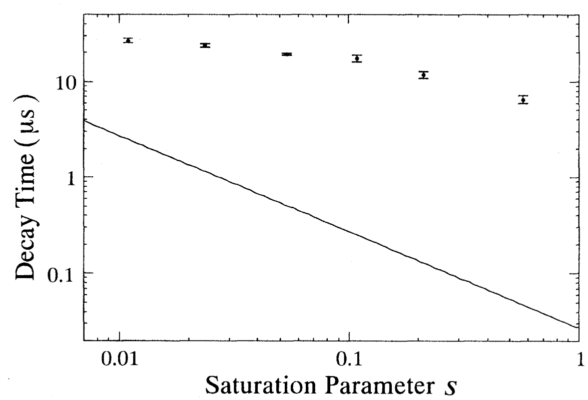

FIG. 2. Dependence of the signal decay time on the saturation parameter. Dots represent the measured decay times. The solid line represents the inverse of the optical pumping rate.

tion of the atomic grating by this interaction can also be observed by this method. The atomic grating will dissipate if the periodic interaction gives rise to heating. However, in the case of cooling, the atomic grating tends to follow the moving optical standing wave, where the term "cooling" means the atomic motion is damped in the frame of moving optical potential. In both cases the time evolution of the atomic grating appears as a decay of oscillating signal.

In our experiment, a cold cloud of ^{87}Rb atoms was produced by a magneto-optical trap (MOT) in a rubidium-vapor cell [21]. The $5S_{1/2}F=2$–$5P_{3/2}F=3$ cyclic transition of the ^{87}Rb D_2 line was used as a cooling cycle. To produce a greater cooling effect, we used polarization-gradient cooling (PGC) [6,7]. First, the magnetic field was turned off quickly. After 5 ms, the detuning of the cooling light was increased, and 5 ms later, its intensity was reduced to $\frac{1}{5}$ of the original intensity. Finally, after 2 ms, the cooling and repumping lights were shut off. In MOT and PGC, $\sigma^+ - \sigma^-$ laser configuration was utilized. The final temperature of the cold atoms was measured by the time-of-flight method [6,22,23] to be 4 ± 1 μK, where the error was mainly due to uncertainty in the determination of the initial size of the molasses.

For this cold sample, we measured the transient response of recoil-induced resonance. Two probe beams intersect inside the sample of prepared cold atoms. Initially, the frequency different δ was kept at zero, and after 20~40 μs, it was rapidly switched to more than 100 kHz. The light interaction time was assured to be sufficiently long to prepare coherence between the momentum states. In this experiment, two probe beams were generated from the same extended-cavity diode laser, and were frequency shifted by individual acousto-optic modulators (AOM). One of these acousto-optic modulators was driven by an rf synthesizer in order to control the frequency difference between the two probe beams. The intensities of the two beams were controlled by another AOM. A typical transient signal is shown in Fig. 1. Here the intensities of probe beams were 12 and 13 mW/cm^2. The beams's crossing angle θ was 14.0°. The probe beams's detuning was fixed to $\Delta/2\pi=+200$ MHz with respect to the $F=2$-$F=3$ transition. The frequency difference of the probe beams was switched from $\delta/2\pi=0$ to 200 kHz in order to observe the signal of damping oscillation.

We first measured the dependency of the decay time of the transient signal on the saturation parameter of probe fields. Figure 2 shows the result, where the solid line represents the inverse of optical pumping rate Γ' $(=s\Gamma)$, where s and Γ are the saturation parameter and a natural width of the atomic excited state, respectively. The intensity, frequency difference, and cross angle of the probe beams were equal to the values in Fig. 1. In order to change the saturation parameter, we changed the detuning $\Delta/2\pi$ from $+15$ to $+110$ MHz. From Fig. 2, one can observe that the decay time increases with decreasing saturation parameter. The induced atomic grating dissipates due to the optical pumping, where the rate is proportional to the saturation parameter. The decay time is expected to become longer as the saturation parameter becomes smaller. A comparison of the solid line and the closed circle in Fig. 2 reflects that the observed decay time is much longer than that expected from the saturation parameter. This result is consistent with the previous result obtained from the width of the recoil-induced resonance [16]. Such a long decay time of the atomic grating or the momentum space coherence can be explained by the energy separation, which is much larger than the recoil energy and the optical pumping rate [5,9].

We also compared the decay time in cases of both blue $(\Delta>0)$ and red $(\Delta<0)$ detuning of probe beams, where $|\Delta|/2\pi=20$ MHz for both cases. Measured transient response signals are shown in Fig. 3. The intensities of probe beams were 5.1 and 5.6 mW/cm^2 and the crossing angle θ was 14.4°. The frequency difference $\Delta/2\pi$ was switched from 0 to 140 kHz. In Fig. 3 the decay times in the cases of blue and red detuning were 14 ± 1 and 10 ± 1 μs, respectively. This implies that the decay time for the blue detuning was longer than that for the red detuning. This difference can be easily understood by considering the effect of stimulated cooling, which occurs only for the blue detuning of probe beams. In the case of red detuning, only the heating effect takes place to dissipate the atomic grating. However, in the case of blue detuning, a stimulated cooling effect is also expected under some conditions. If this effect is valid, the atomic grating tends to follow the moving standing-wave potential with the velocity of δ/q. As a result, the mean time of atoms staying at the potential minimum, where the field intensity is also minimum for the blue detuning, is longer

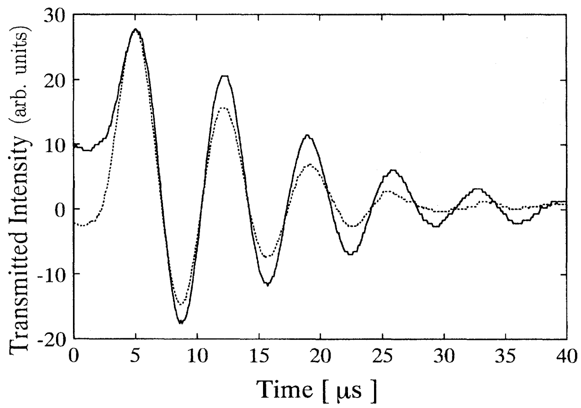

FIG. 3. Signals of transient response for blue and red detunings. The solid and broken curves are the signals for blue detuning $\Delta/2\pi = +20$ MHz and for red detuning $\Delta/2\pi = -20$ MHz, respectively.

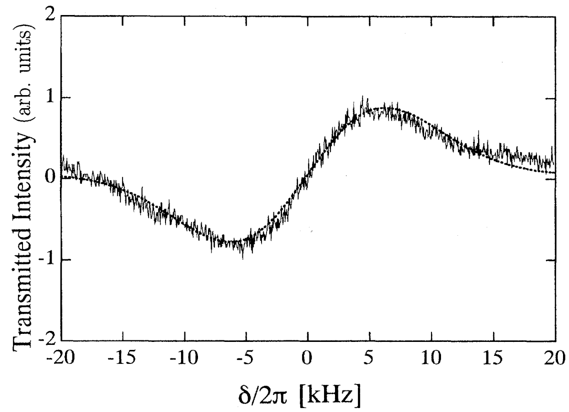

FIG. 4. Signal of the recoil-induced resonance (stimulated optical Compton scattering) for a very cold cloud of ^{87}Rb atoms. The solid curve represents the obtained signal averaged over 16 times of measurements. The broken curve is the theoretical fitting curve.

than the time of staying at the potential maximum. This time difference causes a smaller optical pumping rate for the blue detuning than that for the red detuning. It leads to the difference in the decay time of the transient response. The decay-time difference between blue- and red-detuning cases becomes smaller as the absolute value of detuning becomes larger, because the stimulated cooling effect also becomes smaller.

These two types of time evolution of the atomic grating can be distinguished more clearly by switching the frequency difference δ back to zero again, after observing the first transient response. If the atomic grating moves due to cooling, periodic interaction between the moving atomic grating and the stationary optical standing wave will be generated by this additional switching and the second transient response will be observed. This cannot be observed in the case of heating.

The decay-time measurement provides us with the conditions to achieve the narrow homogeneous width in the temperature measurement using the recoil-induced resonance. The evolution time of the atomic grating corresponds to the coherence time between atomic momentum states, which is related to the homogeneous width of the recoil-induced resonance [16–20]. Therefore, it can be understood that for a narrower homogeneous width, the saturation parameter should be smaller and blue detuning is preferable. Based on this consideration we measured the temperature of cold ^{87}Rb atoms. Figure 4 shows the experimental results. The intensity of the probe beams were 12 and 13 mW/cm^2, and the crossing angle θ was 14.0°. The detuning of the probe beams was fixed to $\Delta/2\pi = +730$ MHz. Under this condition, saturation parameter s becomes 2.5×10^{-4}, which corresponds to the optical pumping rate of 1.5 kHz. The temperature corresponding to the inhomogeneous width 1.5 kHz is lower than 0.1 μK. We fitted the signal shape by the derivative of Gaussian profile and estimated the temperature to be as low as 4.4 ± 0.3 μK. The measurement error was mainly due to the sweep rate of relative frequency $d(\delta/2\pi)/dt = 44$ kHz/ms. This temperature is in good agreement with that measured by the time-of-flight method (4 ± 1 μK).

In summary, we demonstrated the method to directly observe the dynamics of cold atoms. It was confirmed experimentally that this method observes the periodic interaction between the atomic grating and the moving optical standing wave and time evolution of the atomic grating due to this interaction. This method can be a tool for the investigation of the fundamental process in the atomic cooling or in the interaction between atoms and field.

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[1] M. Kasevich and S. Chu, Phys. Rev. Lett. **67**, 181 (1991).
[2] J. Daribard and C. Cohen-Tannoudji, J. Opt. Soc. Am. B **2**, 1707 (1985).
[3] A. Aspect, J. Daribard, A. Heidmann, C. Salomon, and C. Cohen-Tannoudji, Phys. Rev. Lett. **57**, 1688 (1986).
[4] J. Dalibard and C. Cohen-Tannoudji, J. Opt. Soc. Am. B **6**, 2023 (1989).
[5] Y. Castin and J. Daribard, Europhys. Lett. **14**, 761 (1991).
[6] C. Salomon, J. Dalibard, W. D. Phillips, A. Clairon, and S. Guellati, Europhys. Lett. **12**, 683 (1990).
[7] C. Monroe, W. Swann, H. Robinson, and C. Wieman, Phys. Rev. Lett. **65**, 1571 (1990).
[8] P. Verkerk, B. Lounis, C. Salomon, C. Cohen-Tannoudji, J.-Y. Courtois, and G. Grynberg, Phys. Rev. Lett. **68**, 3861 (1992).
[9] J.-Y. Courtois and G. Grynberg, Phys. Rev. A **46**, 7060 (1992).
[10] A. Hemmerich and T. W. Hänsch, Phys. Rev. A **70**, 410 (1993).
[11] A. Hemmerich, C. Zimmermann, and T. W. Hänsch, Europhys. Lett. **22**, 89 (1993).
[12] G. Grynberg, B. Lounis, P. Verkaer, J.-Y. Courtois, and C. Salomon, Phys. Rev. Lett. **70**, 2249 (1993).

[13] A. Hemmerich, C. Zimmermann, and T. W. Hänsch, Phys. Rev. Lett. **72**, 625 (1994).
[14] A. Kastberg, W. D.Phillips, S. L. Rolston, and R. J. C. Spreeuw, Phys. Rev. Lett. **74**, 1542 (1995).
[15] M. Doery, M. Widmer, J. Bellanca, E. Vredenbregt, T. Bergeman, and H. Metcalf, Phys. Rev. Lett. **72**, 2546 (1994).
[16] D. R. Meacher, D. Boiron, H. Metcalf, C. Salomon, and G. Grynberg, Phys. Rev. A **50**, R1992 (1994).
[17] J-Y. Courtois, G. Grynberg, B. Lounis, and P. Verkerk, Phys. Rev. Lett. **72**, 3017 (1994).
[18] J. Guo, P. Berman, B. Dubetsky, and G. Grynberg, Phys. Rev. A **46**, 1426 (1992).
[19] J Guo and P. Berman, Phys. Rev. A **47**, 4128 (1993).
[20] J. Guo, Phys. Rev. A **49**, 3934 (1994).
[21] E. L. Raab, M Prentiss, Alex Cable, Steven Chu, and D. E. Pritchard, Phys. Rev. Lett. **59**, 2631 (1987).
[22] P Lett, R. Watts, C. Westbook, W. Phillips, P. Gouid, and H. Metcalf, Phys. Rev. Lett. **61**, 169 (1988).
[23] D. S. Weiss, E. Riis, Y. Shevy, P J. Ungar, and S. Chu, J. Opt. Soc. Am. B **6**, 2072 (1989).