Observation of recoil-induced resonances and electromagnetically induced absorption of cold atoms in diffuse light

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(Dated: March 22, 2009)

Abstract

In this paper we report an experiment on the observation of the recoil-induced resonances (RIR) and electromagnetically induced absorption (EIA) of cold \textsuperscript{87}Rb atoms in diffuse light. The pump light of the RIR and the EIA comes from the diffuse light in an integrating sphere, which also serves the cooling light. We measured the RIR and the EIA signal varying with the detuning of the diffuse laser light, and also measured the number and the temperature of the cold atoms at the different detunings. The mechanism of RIR and EIA in the configuration with diffuse-light pumping and laser probing are discussed, and the difference between the nonlinear spectra of cold atoms in a diffuse-light cooling system and in a magneto-optical trap (MOT) are studied.

PACS numbers: 42.50.Gy, 42.50.Hz, 32.30.-r

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Laser spectroscopy of cold atoms is a widely-studied subject in atom-light interaction due to the negligible Doppler broadening of cold atoms. With such a feature, laser spectroscopy of cold atoms is widely applied in studying and manipulating of coherent states of atoms and light, quantum information processing, as well as cold atom clocks.

Nonlinear spectra of cold atoms is an important subject in laser spectroscopy of cold atoms which are usually studied in pump-probe configuration. In this configuration, a strong light plays the role of both cooling and pump light. Atoms are cooled to ultra-low temperature by the strong light and also pumped by it. A weak probe laser passes through the cold atom cloud to obtain the nonlinear transmission spectra. Nonlinear spectroscopy of cold atoms in optical molasses as well as magneto-optical trap (MOT) has been widely studied [1, 2, 3, 4, 5, 6], where the counter-propagating laser beams plays the role of both cooling and pump light.

Recently, laser cooling of atoms in diffuse light has shown a great potential in many applications due to its unique features. In diffuse cooling, laser beams do not need any careful alignment or collimation and is therefore very robust. Diffuse cooling is an all-optical cooling technique, and thus has important applications in cold atom clock [7]. Diffuse cooling has a relatively larger velocity cooling range, and can capture more atoms than optical molasses or MOT. The first successful realization of the diffuse cooling directly from atomic vapor was in cesium atoms [8], and followed in rubidium atoms [9].

In diffuse light, an atom with velocity $\vec{v}$ can resonate with the photons from the diffuse laser light, whose propagating directions distribute on an pyramidal surface which have the same angle $\theta$ with respect to $\vec{v}$, and $\theta$ and $\vec{v}$ satisfies the resonate condition:

$$\Delta - \vec{k} \cdot \vec{v} \cos \theta = 0.$$  \hspace{1cm} (1)

Although nonlinear spectra of cold atoms are widely studied in the optical molasses as well as in the MOT, they have been rarely studied in diffuse laser cooling system. In this paper, we report an experiment on the observation of the nonlinear spectra of cold $^{87}$Rb atoms in the diffuse laser light, including the recoil-induced resonances (RIR) and the electromagnetically induced absorption (EIA).

Our experimental setup is shown in Fig. 1. The diffuse laser light is created by a ceramic integrating sphere via Lambertian reflection of two laser beams from two multi-mode optical fibers. The reflectance of the inner surface of the ceramic integrating sphere is about 98% for...
FIG. 1: Experimental setup of the diffuse cooling of $^{87}$Rb atoms. Here, light intensity in the region a is higher than region b.

The 780nm light. A spherical glass cell connected to an ion pump is set inside the integrating sphere. Inner diameter of the integrating sphere is 48 mm and the diameter of the spherical glass cell is 45 mm. Vacuum in the glass cell is about $10^{-9}$ Torr. $^{87}$Rb atomic vapor is filled in the spherical glass cell and is cooled by the diffuse laser light [9].

The cooling laser is supplied by a Toptica TA100 laser system with total output power of $\sim 100$ mW and line-width smaller than 1 MHz that is detuned red of the transition of $5^2S_{1/2}, F = 2 \rightarrow 5^2P_{3/2}, F' = 3$ of $^{87}$Rb atom. A very weak linearly-polarized probe beam of $\sim 1\mu W$ is split from the cooling laser. Such an arrangement keeps the phase between cooling beam and probe beam highly correlated, regardless of the change of environment, such as vibration. A weak repumping laser with total power of 3.8 mW, which is supplied by a Toptica DL100 laser system, is mixed into the cooling beam with a polarizing beam splitter. Frequency of the repumping laser is locked to the transition between $5^2S_{1/2}, F = 1$ and $5^2P_{3/2}, F' = 2$. The cooling beam and the repumping laser beam are injected into the integrating sphere vertically through two multi-mode fibers. Inside the integrating sphere, the cooling and repumping beams become the diffuse laser light by Lambertian reflection. The weak linearly-polarized probe beam ($\sim 20\mu W/cm^2$) propagates through the center of the integrating sphere horizontally to obtain the transmission signal.

We first set the detuning of the cooling laser $\Delta_c = \omega_c - \omega_0 = -3.0\Gamma$ with respect to the
FIG. 2: Experimental probe transmission signal of $^{87}$Rb cold atoms. Here $\Delta_p$ is the detuning of the probe beam. Total power of the two injected cooling laser beams into the integrating sphere is $\sim 36$ mW, and their detuning is $\Delta_c = -3.0\Gamma$. The intensity of the probe laser beam is $\sim 20 \mu$ W/cm$^2$. The strong absorption signal comes from the linear absorption of $F = 2 \rightarrow F' = 3$ transition. The weak amplification and absorption signal near $\Delta_p = -3.0\Gamma \approx -18$MHz is the nonlinear spectrum signal, which can be decomposed into a derivative signal and a pure absorption signal (dotted lines).

cooling transition. Here $\omega_c$ is the frequency of cooling laser, $\omega_0$ is the transition frequency between $5^2S_{1/2}, F = 2$ and $5^2P_{3/2}, F' = 3$, and $\Gamma = 6.056$ MHz is the decay rate of the level $5^2P_{3/2}, F = 3$. Detuning of the probe laser $\Delta_p = \omega_p - \omega_0$ is swept from $-7.0\Gamma$ to $6.0\Gamma$ with respect to the cooling transition by an AOM, where $\omega_p$ is the frequency of the probe laser. The probe transmission signal is shown in figure 2 which includes the absorption of $5^2S_{1/2}, F = 2 \rightarrow 5^2P_{3/2}, F' = 3$ transition near $\Delta_p = 0$ and nonlinear spectra near $\Delta_p = \Delta_c = -3\Gamma$.

With the power of the cooling laser lights (36 mW) and the intensity of the probe laser beam ($\sim 20 \mu$W/cm$^2$) stable, we change the $\Delta_c$ to other values to measure the nonlinear spectra as well as the number and the temperature of cold atoms varying with $\Delta_c$. Figure 3 shows the signal of the nonlinear spectra vs $\Delta_p$ with different $\Delta_c$. The detuning of the probe laser $\Delta_p$ is swept from $-4.5\Gamma$ to $-0.5\Gamma$. Figure 4 gives the number and the temperature of
FIG. 3: Experimental signal of the nonlinear spectra of cold atoms varying with the detuning of diffuse laser light ($\Delta_c$). Detuning of the probe laser beam ($\Delta_p$) is swept from $-4.5\Gamma$ to $-0.5\Gamma$. Total power of the two injected cooling laser beams into the integrating sphere is $\sim 36$ mW, and the intensity of the probe laser beam is $\sim 20$ $\mu$W/cm$^2$.

FIG. 4: Number and temperature of cold atoms for the various detunings of cooling laser $\Delta_c$ corresponding to Fig. 3. Total power of the two injected cooling laser beams into the integrating sphere is $\sim 36$ mW, and the intensity of the probe laser beam is $\sim 20$ $\mu$W/cm$^2$. 
cold atoms vs \(\Delta_c\), which are measured with the same method used in our previous work \[9\]. The temperature is measured from the TOF (time of flight) signal when the diffuse light is switched off. It requires that the probe laser beam is horizontally configured. From Fig. 3 and Fig. 4, we see that the amplitude of the nonlinear spectrum signal is proportional to the number of cold atom when the intensity of diffuse light and the probe light are fixed. The temperature values are below Doppler limit of the \(^{87}\text{Rb}\) atom, which imply some sub-Doppler cooling process may happen in our experimental configuration.

Figure 3 shows that the signal of nonlinear spectra appears always when the frequency of probe laser is near the frequency of cooling laser (the position that \(\Delta_p \approx \Delta_c < 0\)), and when \(\omega_p - \omega_c < 0\), the probe beam obtains a small amplification, whereas when \(\omega_p - \omega_c > 0\), the probe beam is absorbed. The transmission signal of the probe beam is a sum of a derivative signal and a pure absorption signal. We can see that the transmission signal has a trend to separate the derivative signal from the pure absorption signal when \(\Delta_c\) becomes a larger value.

The derivative signal comes from the RIR. It is the derivative of the line-shape related to velocity distribution of cold atoms. This spectrum was first theoretically predicted by Guo et al \[10\] and was experimentally observed in optical molasses \[11, 12\]. Figure 5 shows the scheme of RIR which happens only when the pump and probe beam are counter-propagating and the angle \(\theta\) between the pump and the probe beam is very small. This is because the RIR is a two-photon process with stimulated absorbtion of a photon from pump/probe beam and stimulated emission of a photon to probe/pump beam. Thus the wave-vector of photon from pump beam \((k_c)\), probe beam \((k_p)\), the momentum of atom on \(x\) direction \((p_x)\) and \(y\) direction \((p_y)\) must obey the momentum and energy conservation, which gives the constraint condition

\[
4\pi m(\omega_p - \omega_c) = 2k_p p_x + 2k_c (p_x \cos \theta - p_y \sin \theta) + \hbar (k_p^2 + k_c^2 + 2k_p k_c \cos \theta),
\]

where \(m\) is the mass of the atom. Because \(p_x\) and \(p_y\) have the same Maxwell-Boltzman distribution, it can be proved from the constraint condition that when \(\theta\) is large, the absorption and amplification of the probe beam can attenuate each other’s signal strength (when \(\theta = 90^\circ\) they can totally cancel with each other). Only when \(\theta\) is close to zero does the amplification effect on probe beam become dominate at \(\omega_p < \omega_c\) and the absorption
FIG. 5: Scheme of recoil-induced resonance. Probe laser \((k_p, \omega_p)\) travels along the direction \(e_x\), The other beam \((k_c, \omega_c)\) is one beam of the isotropic laser light which can cause recoil-induced resonances of the atom with the probe laser.

The effect become dominate at \(\omega_p > \omega_c\). Because of the small-angle condition, the main contribution from diffuse light in the integrating sphere to the recoil-induced resonances is the light whose angles to the probe beam are small. That means the light before first-time reflection contributes little to the RIR signal. Another method can also be used to measure the temperature of cold atoms directly from the peak-to-peak separation of the RIR signal [13], but such method can only obtain the temperature of the cold atoms which distribute within the probe beam. In our experiment, as shown in Fig. 2 the two peaks of the RIR signal are separated by \(\sim 500\) kHz, corresponding to the temperature of \(80\) \(\mu\)K, which is within the error range of the measured result of TOF signal in Fig. 4.

The pure absorption part in the nonlinear spectra is the signal of EIA [14, 15], which requires that both of the ground and excited states have Zeeman sub-levels and the quantum number \(F_e > F_g\). Diffuse pump light is quite suitable for the transfer of coherence (TOC) in the EIA to happen [16]. It is because the integrating sphere can randomize the polarization of diffuse laser light [17], then the cold atoms can be pumped with all possible transitions by \(\sigma^+, \sigma^-\) and \(\pi\) lights. Here the absorption peak of the EIA signal is not on the exact position of \(\omega_p = \omega_c\) due to the light shift. The FWHM of the EIA signal generally equals to the decay rate due to time of flight in the probe beam, therefore with the same beam size of the probe light the FWHM should be smaller in cold atoms than in room-temperature atoms due to the much longer interaction time of cold atoms with the probe beam. However, in the experiment with room-temperature atoms there is buffer gas which is mixed into the atomic vapor to make atoms stay longer time in the probe area, so very narrow FWHM of EIA signal with 100 kHz order in the room-temperature can be observed [14, 15]. The EIA can easily happens no matter what the angle between the pump and probe beam is, so
through the light path of probe beam all the beams in the diffuse light that intersect with
the probe beam can contribute to the EIA, including the two expanded beams before diffuse
reflection.

Diffuse cooling is a laser cooling method besides the MOT, therefore it is interesting to
compare the nonlinear spectra between them. The main difference between the diffuse laser
and the $\sigma^+\sigma^-$ configured three-dimensional optical molasses of a MOT is the polarization of
the light field. Cold atoms can have all $\Delta m_F = 0, \pm 1$ transitions corresponding to $\pi, \sigma^+$, and
$\sigma^-$ polarization of the pump light. The light field of a MOT is a three-dimensional optical
molasses, where the polarization of each beam at every position is fixed. We can know
the exact polarization at every position of the light field if we know the exact polarization
of each beam at each position. However, diffuse light is created as well as depolarized by
the Lambertian inner-surface of the integrating sphere [17], so it is a field with random
polarization directions, and the polarization distributes randomly over the space.

Because the polarization at every position of the light field in the center of the MOT
is known, the transition of the trapped cold atoms can be predicted if the direction of
the magnetic field $\vec{B}(x)$ is also known at every position. A well trapped cold atom may
experience periodic light polarization and magnetic field, which may cause different light-
shift and steady-state population among every ground state Zeeman sub-levels. This case
has been studied by Brzozowski et al [6]. They theoretically predicted that the weight of
the $\pi$ transition of the cold atom stands out, which makes the population weight of the
$m_F = 0$ ground-state Zeeman sub-level more than others and suitable for the stimulated
Raman process [1, 2, 3, 4, 5, 6].

Contrarily, in the diffuse laser light the polarization is totally randomized. Since the
diffuse light has only cooling but no trapping effect on atoms, the cold atoms are not well
trapped. Therefore a cold atom in the diffuse laser light can be pumped randomly at every
position with all $\Delta m_F = 0, \pm 1$ transitions no matter what the direction of the quantization
axis (the direction of an strong magnetic field $\vec{B}(x)$) is. This feature makes it difficult to
have significant population difference among all ground state Zeeman sub-levels, which limits
stimulated Raman process but quite suitable for the EIA. The random polarized pump light
can easily have different polarizations with the probe light naturally, which is a necessary
condition for EIA-TOC [16]. Then it is more likely to observe the EIA-TOC of cold atoms
in diffuse laser light.
In conclusions, we have observed the signal of recoil-induced resonances (RIR) and electromagnetic-induced absorption (EIA) of cold $^{87}$Rb atoms in an integrating sphere, where the atoms are cooled and pumped by the diffuse laser light. We analyzed the mechanism of nonlinear spectra of cold atoms in diffuse laser light, and show its differences to the case in MOT. The simple experimental setup and the unique feature of nonlinear spectra of cold atoms in diffuse laser light make the subject is worth to study for the future.

This work is supported by the National Nature Science Foundation of China under Grant No. 10604057 and National High-Tech Programme under Grant No. 2006AA12Z311.

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