Magnetic resonance of atoms passing through a magnetic lattice

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Abstract. We have observed magnetic resonance of Rb atoms passing through a periodic magnetic field produced by a stack of planar arrays of parallel current-carrying wires ("magnetic lattice"). The magnetic resonance occurs between the Zeeman-split sublevels of Rb atoms when the frequency of the field oscillation that the atoms experience equals the transition frequency. A pump laser polarizes Rb atoms with a specific velocity selected by the Doppler effect and a probe laser detects the magnetic resonance. The obtained narrowest resonance lines have widths mainly determined by the transit-time broadening.

1. Introduction
We study resonance transitions in the internal states of atoms passing through a static periodic field. This motion-induced resonance occurs when the frequency of the field oscillation that the atoms experience equals the transition frequency. The principle of the resonance is the same as that of “Okorokov effect” [1] or “resonant coherent excitation” [2], which has been studied extensively using fast ion beams passing through crystals for resonances at high frequencies even in the x-ray regime. Its principle is, however, quite general, and we are interested in its extension to very low energy experiments, such as resonances in the rf or microwave region. If one can precisely control both the atomic motion and field periodicity, it is possible to control the atomic internal states with this resonance technique in the same way as using electromagnetic radiation. The motion-induced resonance is strongly velocity-dependent in nature, and it is particularly worth noting that the internal excitation should occur at the expense of the atomic kinetic energy. These features are not attainable with the standard rf or microwave resonance technique, and we expect that motion-induced resonance will find useful applications as a new type of atom control method. We have already reported motion-induced magnetic resonance using a thin cell of Rb vapor, to which a periodic field is applied with a pair of arrays of parallel current-carrying wires [3, 4]. Its simple experimental setup was satisfactory for the demonstration of motion-induced resonance in the rf region. However, the atoms in the thin cell collided with the surfaces of the cell quite often, which degraded the sharpness of the resonance. For further investigations, we require a longer coherent interaction of atoms with a periodic field, together with an improvement in the signal-to-noise ratio of resonance spectra. We have therefore built a new experimental system, in which an effusive atomic beam of Rb passes through a stack of planar arrays of parallel current-carrying wires ("magnetic lattice") placed in a vacuum chamber. The spatial period of the magnetic field produced by the magnetic lattice is \( a = 1 \text{ mm} \). The atomic velocity \( v \) is about 500 m/s, selected with a collinear laser.
beam using the Doppler effect. The frequency of the field oscillation the atoms see is then \( f = \frac{v}{a} \sim 500 \text{ kHz} \). The laser beam polarizes the atoms by optical pumping, and another probe laser detects magnetic resonance transitions between the Zeeman sublevels of the ground state. As scanning a longitudinal magnetic field, we have observed resonance peaks much sharper and clearer than the previous cell experiments. The narrowest resonance profiles obtained in the measurement have widths almost only determined by the transit time through the periodic field.

2. Experiment
A schematic of the experimental setup is shown in Fig. 1. Rb atoms emerge from an oven held at about 200°C with a broad Maxwell-Boltzmann velocity distribution, from which we selectively use atoms in a narrow velocity range, as described later. The effused atoms are collimated by two holes 2 mm in diameter separated by \( L = 100 \text{ mm} \). The resultant beam divergence is hence 2/100.

A magnetic lattice consists of a stack of printed circuit boards (PCBs), each of which has a periodic current carrying trace. A central part of the magnetic lattice viewed in the beam direction is shown in Fig. 2(a). Each board has a rectangular shape 60 mm in width and 30 mm in length along the beam direction. Totally 11 PCBs are stacked with gaps of 0.8 mm between each other, through which a large fraction of Rb atoms in the beam pass. The angles of the magnetic lattice can be adjusted to accomplish fine alignment between the lattice and the beam.

A schematic diagram of the circuit is shown in Fig. 2(b). A current-carrying copper trace (0.4 mm in width) goes back and forth with a spatial period of \( a = 1 \text{ mm} \). The current at the edges of the board is halved to compensate for the distortion of the periodic field produced by an array of a finite number of current-carrying wires [5]. Figure 2(c) schematically illustrates how this compensation works. As a whole 28 spatial periods are generated. Also refer to Ref. [3] for the details of the periodic magnetic field produced by arrays of parallel current-carrying wires.

A energy level diagram of \(^{85}\text{Rb}\) relevant to the measurement is given in the inset of Fig. 1. A circularly polarized pump laser (wavelength: 780 nm) polarizes the atoms of \(^{85}\text{Rb}\) in the \( F = 3 \) ground state by optical pumping. Magnetic resonance transitions between the Zeeman-split sublevels of this \( F = 3 \) state are detected with a probe laser (wavelength: 780 nm) through its absorption. The polarization of the probe laser is modulated between left- and right-circularly
Figure 2. (a) Central part of the magnetic lattice viewed in the atomic beam direction. (b) Schematic diagram of the circuit on printed circuit boards (PCBs). One PCB corresponds to a green shaded region. PCBs are shown side by side, although they are actually piled up. (c) Compensation for a distorted periodic field by use of two additional correction wires. The calculated magnetic field is a component perpendicular to PCBs at the center between two adjacent PCBs for a current of 1 A.

polarizations at 42 kHz by a photoelastic modulator for the lock-in detection. Resonance signals are observed as scanning a longitudinal magnetic field applied by a pair of coils along the pump beam and thus changing the Zeeman splitting. Other two pairs of coils (not shown in the figure) are used to cancel stray magnetic fields.

Another important role of the laser beams is to select atoms within a narrow velocity range from a broad Maxwell-Boltzmann distribution using the Doppler effect. The laser frequency is stabilized to one of the resonance lines of saturation absorption spectrum of $^{85}$Rb and is further shifted using an acousto-optic modulator. The resultant detuning of the laser frequency from the $F = 3 \rightarrow F' = 4$ cyclic transition determines a selected velocity. The width of the selected velocity distribution is estimated to be about 5 – 10 m/s, which is mainly determined by the natural linewidth (6 MHz) of the $F = 3 \rightarrow F' = 4$ transition.

3. Results
Figures 3(a) and (b) demonstrate motion-induced resonance for atoms with a velocity of 512 m/s selected by the laser detuning of 656 MHz. The x- and y-axes are the scanning longitudinal magnetic field and the lock-in signal of the transmitted probe laser intensity, respectively. A current of 5 mA generated a periodic magnetic field with an amplitude of 0.8 $\mu$T at the center between two adjacent PCBs. The periodic magnetic field and the lasers were weak enough to obtain the narrowest signals in the present experimental setup. The traces were averaged 1000 times over 500 s. As clearly seen in the figures, a motion-induced resonance signal appears only when the periodic magnetic field is applied. The signal is peaked at 510 kHz, in a good agreement with the expected value of 512 kHz. Note that the large peaks seen in both figures at the zero longitudinal magnetic field are so-called “Hanle resonances”, which were produced.
by a residual transverse magnetic field.

One may notice that there are two small dips in Fig. 3(a). They are also signals of motion-induced resonance for atoms with different velocities. We intended to observe atoms with a velocity of 512 m/s through the $F = 3 \rightarrow F' = 4$ cyclic transition, but actually, although smaller in number, atoms with a velocity of 368 m/s or 417 m/s were additionally observed through the transition of $F = 3$ to $F' = 2$ or 3, respectively. Note that the lasers had different detunings with respect to these transitions and hence selected different velocities as well. The two small signals change in the opposite direction compared to the main resonance peak, because the laser transmission decreases for these transitions when motion-induced resonance occurs, while it increases for the $F = 3 \rightarrow F' = 4$ transition.

The line broadening due to the time of flight through the magnetic lattice, the fundamental limit of the linewidth in our setup, is estimated to be 16.3 kHz (full width at half maximum) [6], which is the main contribution to the obtained linewidth of 20 kHz. This implies that other factors contributing to the linewidth, such as dephasing caused by the collisions of atoms with the printed circuit boards, are not critical. Among them, however, the finite width of the velocity selection certainly causes an additional broadening, estimated to be about 10% increase from the transit-time broadening. The inhomogeneity of the longitudinal magnetic field is another probable reason for the broadening.

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