Motion-Induced Magnetic Resonance of Rb Atoms in a Periodic Magnetostatic Field

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We demonstrate that transitions between Zeeman-split sublevels of Rb atoms are resonantly induced by the motion of the atoms (velocity: \( \sim 100 \text{ m/s} \)) in a periodic magnetostatic field (period: \( 1 \text{ mm} \)) when the Zeeman splitting corresponds to the frequency of the magnetic field experienced by the moving atoms. A circularly polarized laser beam polarizes Rb atoms with a velocity selected using the Doppler effect and detects their magnetic resonance in a thin cell, to which the periodic field is applied with the arrays of parallel current-carrying wires.

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By applying an electromagnetic (EM) wave to an atom at rest, one can resonantly induce transition between two atomic energy levels whose frequency difference coincides with the EM wave frequency. This resonance transition is one of the most extensively studied and widely utilized phenomena in atomic physics and also in other various fields. Also in the reversed configuration, that is, by an atom moving in a static periodic field, an internal transition can be made when the periodic perturbation experienced by the atom has a frequency equal to the transition frequency. The resonance transition of this kind, quite simple in principle and applicable to any particle with internal states, however, has been clearly demonstrated only in the phenomenon called “resonant coherent excitation” (RCE) \(^1\) using channelled fast ion beams in periodic electric fields of crystals. RCE has attracted much attention \( ^2 \) \( ^3 \) \( ^4 \) \( ^5 \) \( ^6 \) \( ^7 \) \( ^8 \) since the first proposal by Okorokov \( ^9 \). Recent progress made by using the high-energy beams of highly charged ions shows the possibility of high-resolution spectroscopy of highly charged ions in an x-ray region of keV or \( 10^{18} \text{ Hz} \). \( ^8 \) The order of this transition frequency is determined by an ion velocity (\( \sim 10^8 \text{ m/s} \)) and a lattice constant (\( \sim 10^{-10} \text{ m} \)).

We report in this Letter on the resonance transition that is based on the same principles as RCE but is induced by a different type of interaction in a quite different energy range of neV or \( 10^5 \text{ Hz} \): magnetic resonance between the Zeeman sublevels of Rb atoms with a \( z \) velocity component \( v_z \) of \( \sim 100 \text{ m/s} \) in a static magnetic field that is periodic in the \( z \) direction (period: \( a = 1 \text{ mm} \)). This resonance transition, called motion-induced resonance in this Letter, was observed in a thin cell containing Rb vapor, with the periodic magnetic field applied with the arrays of parallel current-carrying wires sandwiching the cell. The atoms with a velocity selected using the Doppler effect were polarized by optical pumping with circularly polarized laser light slightly detuned from the \( D_2 \) line. The magnetic resonance between the ground state sublevels was optically detected with the same laser beam. We confirmed that the resonance occurs when the Zeeman splitting frequency coincides with \( v_z/a \), namely the frequency of the field experienced by the moving atoms. We successfully obtained the resonance spectra very similar to those of standard rf magnetic resonance. Our clear demonstration of motion-induced resonance shows that experiments using slow atoms and artificial periodic fields are useful to study the fundamental dynamics of this kind of resonance compared to RCE experiments, which involve complicated atomic processes in solid. We also consider that this experiment is the first step to extend the study to well-controlled atoms in the fields of precise- and small-period structures with the help of advancing surface nanofabrication technologies and progressing atom control and manipulation techniques, particularly near surfaces, such as atom chips, \( ^9 \) and quantum reflection \( ^9 \). These studies will reveal a new aspect of motion-induced resonance, and may lead to the development of unique techniques alternative to EM wave methods to control the internal states and also the associated motional states (see the next paragraph) of atoms (and any particle with internal states) near surfaces.

We first discuss the basic properties of motion-induced resonance from a perspective of the momentum and energy of an atom in analogy to atom-EM-wave resonance to get a better understanding rather than the simple picture that the resonance transition occurs when the frequency of the field experienced by an atom coincides with the transition frequency. When the internal state of an atom is excited in an EM standing wave, the momentums and energies of the atom before and after excitation are related as

\[
m v'_z = m v_z \pm \hbar / \lambda, \quad E' + m v'^2/2 = E + m v^2/2 + \hbar \nu, \quad (1)
\]

where \( v_z (v'_z) > 0 \), \( E(E') \), and \( v(v') \) are, respectively, the velocity in the \( z \) direction, the internal energy of the atom, and the speed of the atom with a mass of \( m \) before (after) excitation by the EM wave with a frequency of \( \nu \) and a wavelength of \( \lambda \) (note \( v^2 = v_x^2 + v_y^2 + v_z^2 \)). \( \hbar \) is Planck’s constant. The sign + (−) in the momentum relation corresponds to the excitation induced by one of the counterpropagating waves that is running...
The resonance condition \( \Delta = \frac{h}{\lambda} \) may be used to control the motional state of atoms by inducing resonance. In fact, although not having been verified experimentally, it is justified in the case of motion-induced resonance it is justified that, in an inertial frame where the static periodic field is at rest, one sets \( \nu = 0 \) while keeping \( \lambda = a \) in Eq. (1). The corresponding relations are

\[
mv_z' = mv_z \pm h/a, \quad E' + mv^2/2 = E + mv^2/2. \tag{2}
\]

One has to take the lower sign in the case \( \Delta E > 0 \). The resonance condition \( \Delta E = hv_z/a \) is then deduced. From this discussion it can be said that the transition is caused purely by the Doppler effect, and the internal energy is increased at the expense of the kinetic energy. In addition, as a consequence of the field periodicity, the atom momentum should change by \( h/a \) in the transition (note that this momentum change is transferred to the periodic structure that produces the periodic field). This fact, although not having been verified experimentally, may be used to control the motional state of atoms by motion-induced resonance.

The experiment was performed with a thin quartz cell (inner dimension: \( 48 \times 10 \times 0.2 \) mm), whose cross section is depicted in Fig. 1(a). The evacuated cell contains Rb vapor with a density of \( \sim 10^9 \) cm\(^{-3} \) at room temperature, where the Doppler broadening for the Rb \( D_2 \) transition at 780 nm is about 250 MHz (half width at half maximum: HWHM). The natural linewidth of the \( D_2 \) line is 3 MHz (HWHM). An external cavity laser diode, whose linewidth was estimated to be 1 MHz, was frequency stabilized to the \( F=3 \rightarrow F'=4 \) transition of the \( D_2 \) line of \(^{85}\text{Rb} \) (see Fig. 1(b)). The uncertainty of the laser frequency was at most a few MHz. The laser frequency was then shifted (see Fig. 1(b)) with an acousto-optic frequency shifter in the range of 123-203 MHz to select an atom velocity in the range of \( v_z = 96 \) to 158 m/s through the \( F=3 \rightarrow F'=4 \) transition. The laser beam was finally made right-circularly polarized and irradiated the whole volume of the narrow cell gap to polarize the \( F=3 \) ground state of atoms with a velocity component \( v_z \) in the laser direction. Note that atoms with a velocity \( v_z + 94 \) or \( v_z + 144 \) m/s were also polarized through the transition \( F=3 \rightarrow F'=3 \) or \( F'=2 \). However, they are fewer than atoms with a velocity \( v_z \), and also tend to become off resonant with the laser due to hyperfine pumping to the \( F=2 \) ground state via the excited states. Therefore they should not significantly contribute to the signal. A periodic magnetostatic field (period: \( a = 1 \) mm) was applied to the cell with two printed circuit boards (PCBs) (100 \( \times \) 30 mm) sandwiching the cell. The current direction and the current-carrying trace on a PCB are shown in Figs. 1(c), (d), respectively. The details of the produced periodic field are described in the next paragraph. A longitudinal magnetic field applied along the laser beam with a set of Helmholtz coils (40 cm diam) was slowly scanned to cause the Zeeman splitting by 4.67 kHz per \( \mu \text{T} \) between the adjacent sublevels of the \( F=3 \) state. The resonant transitions between the sublevels occurred when the splitting frequency coincided with the frequency of the field experienced by the atoms under observation. The resonance was detected by monitoring the transmitted laser intensity, which increase corresponded to typically \( 10^{-5} \) to \( 10^{-6} \) variation of the laser beam intensity. For better detection sensitivity, we employed a lock-in detection scheme by switching on and off the periodic field at 4 kHz, and further averaged the lock-in signals. The cell, PCBs and coils were enclosed in a magnetic shield (65 \( \times \) 65 \( \times \) 65 cm), which reduced the Earth’s and other environmental magnetic fields to the order of 0.1 \( \mu \text{T} \). To perform a standard rf magnetic resonance experiment for comparison with motion-induced resonance, the PCBs were removed and then resonance profiles were recorded as a transverse oscillating magnetic field was applied with another set of Helmholtz coils (15 cm diam).

The basic behavior of the field produced by the PCBs in the cell is described analytically, using the coordinate system defined in Fig. 1(c), as

\[
B_z = B_0 \exp(-kd) \cosh(kx) \sin(kz), \quad B_y = 0, \\
B_z = B_0 \exp(-kd) \sinh(kx) \cos(kz). \tag{3}
\]
$B_0$ is a constant proportional to the current, and $k = 2\pi/a$. The current flows on the surfaces located at $x = \pm d$; $d$ was measured to be 0.65 mm. Figure 2 shows the numerically calculated periodic magnetic field produced by the actual PCB current. At the center of the cell ($x = y = 0$ mm), the $x$ component of the field $B_x$ behaves as $\sin(kz)$ with an amplitude of 65 $\mu$T/A, although its baseline declines slightly along the $z$ direction due to the finite number of current wires [9] as seen in the upper graph in Fig. 2. $B_z$ is equal to zero, while $B_y$ has a small value of 1 ~ 2 $\mu$T/A, which is produced by the current flowing in the $z$ direction on the PCB edges at $y = \pm 15$ mm. Near the cell surfaces at $x = \pm 0.1$ mm, $B_x$ is larger by 20% than at the center as seen in the lower-right graph in Fig. 2 while $B_z$ oscillates as well with an amplitude of 43 $\mu$T/A. This longitudinal $B_z$ field experienced by moving atoms is so rapidly oscillating, however, that it does not affect resonance profiles in the experiment. Note that the sandwiching configuration of the PCBs reduces a strong dependence of the field strength on $x$ around $x = 0$, contrary to an exponentially $(1/e$ constant: $a/(2\pi))$ decreasing field with increasing distance from a single periodic source [11]. Finally, near the cell edges at $y = \pm 5$ mm the produced field is basically the same as described above. As a summary, the produced periodic field can essentially approximate to a sinusoidal field oscillating in the $x$ direction with a constant amplitude over the cell. It is therefore expected to obtain motion-induced resonance profiles similar to rf resonance ones. We finally note that the calculated field strength has an uncertainty of about $\pm 10\%$, which is mainly due to an uncertainty in the position of the PCB current ($d = 0.65 \pm 0.02$ mm).

Figure 3(a) shows motion-induced magnetic resonance spectra recorded as a function of the longitudinal magnetic field from about $-80 \mu$T to $+80 \mu$T. The laser frequency detunings are 203 MHz, 163 MHz, and 123 MHz, corresponding to selected velocities of 158 m/s, 127 m/s, and 96 m/s, respectively. The two resonance peaks are clearly observed, almost symmetric with respect to the zero magnetic field. One may notice the slightly larger resonance signals in the negative longitudinal field than in the positive field, noticeable also in rf resonance spectra (see Fig. 3(b)). We consider that this is attributed to a small difference in the laser absorption probability due to the Zeeman shifts of sublevels. As the laser detuning (and hence the selected velocity) decreases, the resonance peaks move toward the zero magnetic field (and hence the zero Zeeman splitting) as seen in Fig. 3(a). We derived with an uncertainty of a few kHz the sublevel splitting $f$ at which the resonance peak was centered with the help of Lorentzian fittings, and plot it as a function of selected velocity $v_z$ in Fig. 3(b). As clearly seen, the resonance frequency is proportional to the atom velocity as $f = v_z/a$ ($a = 1$ mm), which is the resonance condition of motion-induced resonance.

The spectral width was found to be mainly determined by the light intensity and the periodic field strength from...
measurements performed by changing each parameter independently. Figure 4(a) shows narrower linewidth for a weaker laser intensity and PCB current than in Fig. 3(a). The linewidth was still decreasing with decreasing laser intensity and PCB current in the ranges of the intensity and current of Fig. 4(a), although we could not reduce them further due to the limit of detection sensitivity in the present experimental setup. The width (HWHM) of the spectrum in Fig. 4(a) is 56 kHz (12 µT), corresponding to an effective transverse spin relaxation time of 3 µs. This relaxation time is of the same order as the mean free time between collisions of atoms with the cell surfaces, where the spin polarization is supposed to be completely destroyed. It is interesting to point out that the spectral width should become much narrower with decreasing laser intensity than that determined by the mean free time, because of selective polarization and detection of atoms that have long free flight times (and hence have long spin relaxation times).

We show in Fig. 4(b) a magnetic resonance spectrum recorded in the standard magnetic resonance experiment, namely recorded with a transverse rf magnetic field oscillating at 156 kHz, for the laser intensity and field amplitude similar to the case of Fig. 4(a). The laser detuning is the same as that in Fig. 4(a), although the selected velocity dependence is negligible in rf resonance. As seen in this figure, the shape of the spectrum is basically identical to that of the motion-induced resonance as we have expected, while its width is somewhat smaller (50 kHz HWHM). This small difference may probably be attributed to additional factors that increase the resonance width in motion-induced resonance in our experimental setup. One factor is the finite width in selected velocity, originating from the natural linewidth and the laser-power broadening of the $D_2$ absorption line. The non-periodic transverse magnetic field produced by the PCB current is another factor, about a few µT/A in the $x$ and $y$ directions. The current in the wires connecting the two PCBs and the PCBs to a power supply also produces a transverse field of the same order.

In conclusion, we have clearly demonstrated that magnetic transitions are resonantly induced in an artificial periodic magnetic structure by the motion of Rb atoms having thermal energy at room temperature. We have confirmed that the magnetic resonance occurs when the Zeeman splitting of the ground state of Rb atoms corresponds to the atom velocity divided by the field period. Resonance profiles quite similar to those of standard rf magnetic resonance have been obtained. We finally emphasize that motion-induced resonance, whose principles have been demonstrated only in so-called resonant coherent excitation by using channeled fast ion beams in crystal fields, is a general phenomenon that occurs for various scales of field periods and kinetic/transition energies of particles, and also for various types of particles and interactions. Our demonstration opens the door to a new class of experiments related to this resonance for slow atoms in artificial periodic fields.

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FIG. 4: (a) Motion-induced resonance spectrum obtained for a laser detuning of 203 MHz and hence a selected velocity of 158 m/s. The PCB current is 0.08 A and the estimated periodic magnetic field amplitude at the cell center is 5.2 µT. (b) rf resonance spectrum obtained for an rf frequency of 156 kHz and amplitude of 5.0 µT. The laser detuning is the same as that in (a). In (a) and (b) the laser intensities are almost equal, $40 \mu W/cm^2$ with ±20% uncertainties. The signal scales are roughly the same.