Ionizing Collisional Rate of Metastable Rare-Gas Atoms in an Optical Lattice

Hideyuki Kunugita, Tetsuya Ido, and Fujio Shimizu
Department of Applied Physics, University of Tokyo, Bunkyo-ku, Tokyo 113, Japan
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Ionizing collisional rate of metastable krypton and argon atoms in an optical lattice k_{lattice} is compared with that in free space k_{free}. Reduction of the collisional rate is observed for krypton atoms. However, the magnitude of reduction is no more than a factor of 2 at the laser detuning of 7 GHz. The ratio $k_{\text{lattice}}/k_{\text{free}}$ is found to change proportional to the square root of the excitation rate of atoms from the $1s_5$ metastable state to the $2p_9$ state by the lattice laser. The mechanism that prevents a larger reduction is discussed. [S0031-9007(97)03700-9]

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Recent development of laser cooling and trapping of neutral atoms has attracted various scientific and technical interests [1]. Many applications of laser cooled atoms, such as nonlinear optical effects or atom interferometries, benefit with a higher atomic density. The atomic density in a trap is generally limited by collisions of atoms in the trap. In the most commonly used magneto-optical trap (MOT), the collision cross section is extremely large due to the existence of red-detuned trapping lasers that induces an attractive resonant-dipole interaction. Various techniques to reduce these light induced collisions were proposed and demonstrated [2–5]. To cool an atomic cloud several planar laser beams illuminate the cloud from different directions. This produces a spatially varying pattern of the laser field, and in turn, a pattern of spatially varying optical-dipole potential which is called an optical lattice [6]. The optical lattice with four laser beams is particularly interesting, because the three-dimensional pattern of the potential does not change with relative phase fluctuation of each laser beam. Since atoms are trapped in the minima of the dipole potential, one may consider that collisions are suppressed in an optical lattice. To date detailed comparison of collisions in an optical lattice has not been reported. We studied ionizing collisions of metastable argon and krypton atoms in the $1s_5[(n+1)s : {}^3P_2]$ state. We observed reduction of collisions only for krypton when the lattice laser was sufficiently detuned [7]. For argon the ionizing collisional rate was always larger than that of free atoms.

This unexpected result arises that a real optical lattice is not an ideal single-surface periodical potential. In an usual optical lattice the angular momentum F of the atom is not zero, and there are $2F+1$ potential surfaces corresponding to $2F+1$ magnetic levels. Atomic state changes as a result of optical pumping by the lattice laser. Since each magnetic level has a different potential surface, the optical pumping induces a complicated atomic motion. To elucidate the motion of atoms in the lattice let us consider the case that was used in the present experimental work. Figure 1 shows the configuration of the optical lattice in our experiment. The lattice laser beams were sent from four tetrahedral directions $(\pm x, \mp y, z)$ and $(\pm x, \pm y, -z)$, and their polarization was in the x-y plane for all beams [8]. Figure 2 shows the cross sections of potential surfaces along the z and x-y directions for five levels, A–E, that correspond to the $2F+1=5$ magnetic levels of the $1s_5$ state. Minimum positions of the lowest energy level A are shown by circles in Fig. 1. The laser field is circularly polarized at the minimum point. Black and open circles in the figure distinguish the direction of the circular polarization. At sufficiently low temperature atoms are trapped in minima of the lowest potential A. If an atom absorbs a lattice photon and is excited to the $2p_9[(n+1)p : {}^3D_3]$ level, it can decay spontaneously to any one of the five levels A to E. Its probability is in decreasing order from A to E. If the atom decays to either A or B, it stays more likely in the same lattice site, because both potential surfaces take minimum value at the same spatial point. However, if the atom decays to C, D, or E level, it is accelerated towards the adjacent site. Once freed from a potential-minimum site the atom can collide with other tapped atoms. Because the trajectory of the moving atom

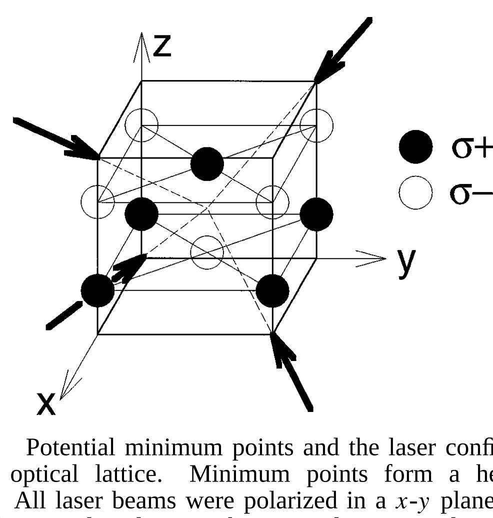

FIG. 1. Potential minimum points and the laser configuration of the optical lattice. Minimum points form a hexagonal lattice. All laser beams were polarized in a x-y plane. Black and white circles distinguish two polarization directions of circularly polarized optical electric field at the minimum point.

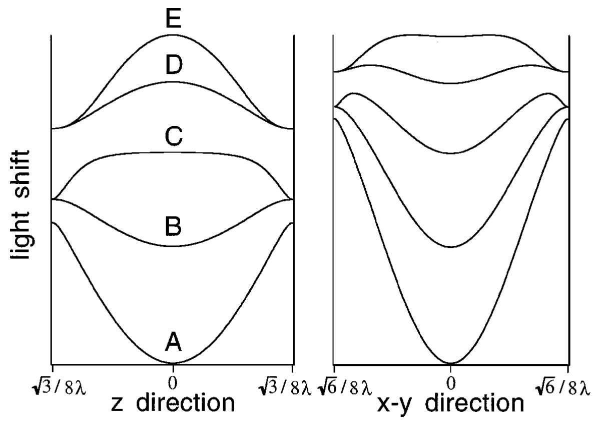

FIG. 2. The potential curves along z and $\pm(x \pm y)$ axes. The levels A, B, C, D, and E correspond to the $M_F = -2, -1, 0, 1,$ and 2 levels at the minimum potential point, respectively.

is restricted in space by the optical potential that forms the lattice, its collisional rate is larger than that of atoms in the MOT. The moving atom falls back eventually to the potential A by optical pumping. When it happens to fall in the lattice site that is occupied by another atom, two atoms will collide in a short time. This loss mechanism is also large, because the volume of a single lattice cell $V_l = (3^{3/2}/32)\lambda^3$ is much larger than the volume of an atom. The collisional rate constant is approximately equal to $V_l \gamma_{\mathrm{op}}$, where γ_{op} is the optical pumping rate from the level A to either C, D, or E level. In free space the collisional rate constant is a product of the collisional cross section σ_i and the atomic velocity v. At a low temperature the rate constant $k_{\mathrm{free}} = \sigma_i v$ is approximately constant, and has a value $10^{-10} \sim 10^{-11}$ $\mathrm{cm}^3\,\mathrm{s}^{-1}$. Since the wavelength λ of the laser is 800 nm, this means that the collisional rate in an optical lattice is larger than that of free space unless the optical pumping rate γ_{op} is smaller than $10^2 \sim 10^3$ s^{-1}. Such a low pumping rate is achieved only when the laser detuning is extremely large compared to the natural linewidth of the cooling transition $1s_5$-$2p_9$.

The experimental setup of making an optical trap of metastable argon or krypton was described elsewhere [5]. Metastable atoms were produced by a weak discharge in a glass tube and extracted from a hole on the anode side. To enhance the flux density, atoms were deflected and collimated by a laser resonant to the cooling transition [9]. The atoms passed through a Zeeman slowing stage and were trapped at the end of the slowing stage by using a standard MOT with three pairs of standing waves [10]. After atoms were accumulated in the trap for approximately 0.5 s, the atomic source was shut off by a mechanical shutter, simultaneously as the quadrupole magnetic field that formed the MOT was switched off with a time constant of 0.2 ms. To cancel out stray magnetic field three pairs of Helmholtz coils were placed around the trapping chamber. Their current was adjusted so that the temperature of trapped atoms at the end of the cooling procedure became minimum. The detuning of the trapping laser was changed from –10 to –34 MHz, and after 1 ms the laser intensity was reduced to $1/10$ for a period of 1 ms. This cooled the trapped atomic cloud to the temperature of approximately 10 μK as a result of polarization-gradient cooling [11]. Then the trapping laser was switched off and the lattice laser was introduced. The lattice laser was kept on for 100 ms, and then switched off. Collisions of metastable rare-gas atoms in the trap were predominantly ionizing collision with a small fraction of associative ionizing collisions [5]. Rare gas ions that were created by binary collisions of atoms in the trap were collected on a microchannel plate detector (MCP) (Hamamatsu F4655) that was placed at 60 mm side of the trap. The potential of the front surface of the detector was –2.8 kV to count only ions that originated predominantly from atoms in the lattice. To measure the velocity distribution of atoms in the lattice by time-of-flight technique an electron multiplier (Hamamatsu R2362) was placed 30 cm below the trap. It was used to determine the temperature of atoms when the lattice laser was switched off. The size and pattern of the atomic cloud were monitored by a CCD camera. The temporal variation of the ion count of the MCP was recorded on a multichannel scaler (Stanford Research Systems SR430) with the time resolution of 41 μs. The entire procedure from the accumulation of atoms in the MOT to the switching off of the lattice laser was repeated approximately 10^3 times. Figure 3 shows typical data accumulated in the multichannel scaler. It shows the case of the krypton lattice with the detuning of 7 GHz

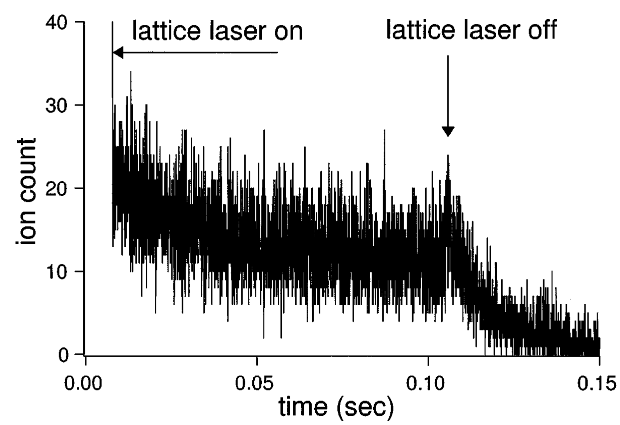

FIG. 3. Typical temporal change of ion counts. The quadrupole magnetic field was switched off at $t = 0$ simultaneously as the laser detuning and intensity were changed for the further cooling by the polarization gradient cooling. The laser was switched at 8 ms point from the MOT configuration to the lattice configuration. The lattice laser was on from 8 to 105 ms, and then switched off. The count rate is seen to increase by 40%, showing that the collisional rate is smaller in the lattice than in free space by the same amount. The detuning δ was 7 GHz.

and a power density of 180 $(\mathrm{mW/cm^2})$/beam. The ion count dropped by the factor of 10 to 30 when the laser was switched from the MOT configuration to the lattice configuration (at the time of 0.05 s in the figure). The count decreased further while the temperature of the atomic cloud stabilized to the equilibrium condition that was determined by the lattice laser. The transient time was approximately 40 ms at the excitation rate $\gamma_{\mathrm{ex}} \approx 2.3 \times 10^3\ \mathrm{s^{-1}}$. The time decreased with $\gamma_{\mathrm{ex}}^{-1}$ as it was expected from the rate of the spontaneous emission that cooled or heated the cloud after the switching from the MOT to the lattice [12]. The transient was not observed at a higher γ_{ex} above $10^5\ \mathrm{s^{-1}}$. When the lattice laser was switched off, the count jumped up showing that the collisional rate was higher for free atoms. After the switching off of the lattice laser (0.105 s) the ion count dropped rapidly as the atomic cloud expanded. When the detuning was smaller, or in all cases for argon, the count decreased when the lattice laser was switched off. The ratio of the count rates before and after the switching of the lattice laser gives the ratio of the collisional rate constant in the lattice k_{lattice} and in free space k_{free}.

We repeated the above procedure for various laser detunings from 160 MHz to 7 GHz, and the laser intensities from 4.9 to 200 m $(\mathrm{W/cm^2})$/beam. The excitation rate of the atom from the $1s_5$ state to the $2p_9$ state is

$$\gamma_{\mathrm{ex}} = \gamma \frac{\Omega^2/4}{\gamma^2/4 + \delta^2} \approx \gamma \frac{\Omega^2/4}{\delta^2}, \qquad (1)$$

where γ is the natural decay rate, δ is the detuning, and Ω is the Rabi angular frequency of the $1s_5$-$2p_9$ transition. The square of the Rabi frequency Ω^2 is proportional to the laser intensity. The optical pumping rate $\gamma_{A\rightarrow i}$ from the level A to other magnetic level, $i = B, C, D$, or E, is also proportional to γ_{ex}. Therefore, at a large detuning, $\delta \gg \gamma$, the optical pumping rate is inversely proportional to the square of the detuning. We plotted the ratio $k_{\mathrm{lattice}}/k_{\mathrm{free}}$ as a function of the excitation rate γ_{ex}. The result is shown in Fig. 4(a) for argon and in Fig. 4(b) for krypton. Both for argon and krypton the ratio decreased with γ_{ex}. The numerical value was obtained by dividing the average count rate during the 10 ms before the switching by the count rate immediately after the switching. The latter was deduced by fitting the data during the 20 ms after the switching with an exponential function. The error bar shows the 3σ range of the statistical error of each measurement. For argon it approached to one at around $\gamma_{\mathrm{ex}} \approx 3 \times 10^3\ \mathrm{s^{-1}}$, however, never decreased below one. For krypton the ratio kept decreasing when γ_{ex} was reduced below unity at $\gamma_{\mathrm{ex}} \approx 3 \times 10^3\ \mathrm{s^{-1}}$. The minimum value was approximately 0.7 at $\gamma_{\mathrm{ex}} \approx 10^3\ \mathrm{s^{-1}}$. Data points fit on a single straight line regardless of the laser power density. This supports that the dominant mechanism of collisions of atoms in the lattice was site hopping caused by the optical pumping of atoms

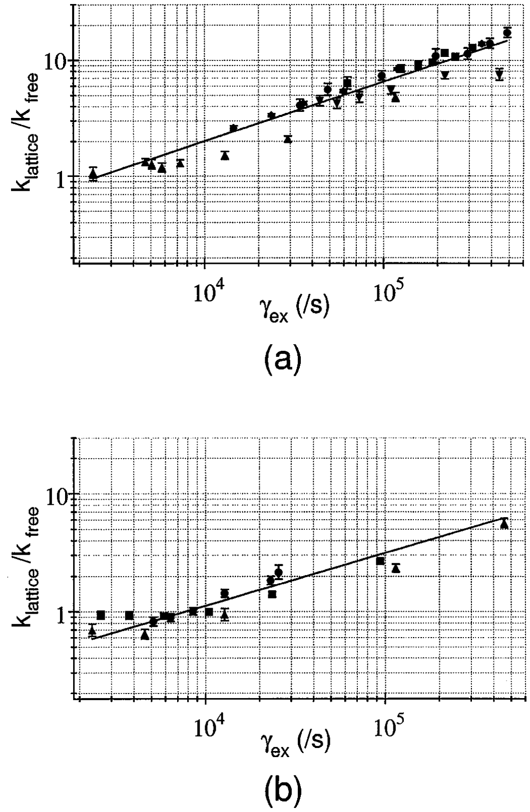

FIG. 4. The excitation rate γ_{ex} dependence of $k_{\mathrm{lattice}}/k_{\mathrm{free}}$ for argon (a) and krypton (b). Experimental data points were obtained either by changing the laser power at a fixed detuning, by changing the detuning at a fixed power density, or by changing both parameters at a fixed Ω^2/δ. In (a), ◆: 44 mW and 160 MHz–1.4 GHz, ■: 9–45 mW and 300 MHz, ▼: $\Omega^2/\delta = \text{constant}$, 45 mW and 800 MHz–4.5 mW and 80MHz, ●: 4.9–70 mW and 300 MHz, ▲: 186 mW and 1–7 GHz. In (b), ■: 150 mW and 1–6 GHz, ▲: 183 mW and 0.5–7 GHz, ●: $\Omega^2/\delta = \text{constant}$, 40–200 mW and 1–5 GHz. The power means the power density per square centimeter per beam. The error bar shows the 3σ statistical error of the measurement of each point.

from the level A to inverted levels C, D, or E. The pumping-rate dependence of the relative collisional rate was 0.49 ± 0.035 for Ar and 0.45 ± 0.022 for Kr, or very close to the square root dependence.

To investigate this square-root dependence we did numerical simulation of hopping atoms among lattice sites. The result shows that, when the excitation rate γ_{ex} is large, the square-root dependence is caused as a result of one-dimensional movement of atoms in the lattice. When γ_{ex} is small, the slow change of the $k_{\mathrm{lattice}}/k_{\mathrm{free}}$ is mainly due to the lowering of the potential height of the lattice. The atom that is excited to C–E levels moves from one potential-minimum site to the adjacent one through one of six narrow paths that pass a saddle point of the lattice potential. The potential height at the saddle point along z axis is lower than that along the x-y directions. Therefore, we can expect that the motion of the moving atom is close to the one-dimensional hopping motion along z axis. When γ_{ex} is large, the atom falls back quickly to the A level after it is excited to one of the B–E levels. The moving distance during the single excitation/deexcitation process is short. In such a situation the number of new lattice sites that are covered by the hopping atom increases proportional to the square root of the number of the excitation cycle. Since two atoms in the same lattice site collide quickly, atoms are separated evenly in the lattice in a short time after the lattice formation. As a result the collisional rate becomes smaller than that when atoms are randomly distributed. When the excitation rate is small, the excited atom moves a longer distance. Therefore, the probability to fall in an old site is small. However, in the present experimental condition the small γ_{ex} means a lower potential height. This makes atoms easier to move, and a higher probability of collisions. The result of our semiclassical numerical simulation agrees quantitatively with the experimental result. The detailed discussion will be published separately.

In conclusion, we have demonstrated for the first time the suppression of collisions of cold atomic gas in an optical lattice. The dynamics of collisions in the lattice show that to obtain a large reduction a higher laser power density and detuning much larger than several GHz are required. Furthermore, because of the square-root dependence of k_{lattice} on γ_{ex}, it is more difficult to achieve reduction at a higher atomic density.

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