Suppression and Enhancement of Collisions in Optical Lattices

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In a three dimensional optical lattice for metastable xenon we observe the dynamical effects of the optical potential on Penning ionizing collisions between atoms. Enhancement of collisions over that for free atoms is observed at short times after the atoms are loaded into the lattice. After the atoms thermalize and localize into the potential wells, we observe a suppression of the collisions by as much as a factor of two. From our measurements and a simple model we are able to extract an estimate of the rate at which atoms "hop" between wells.

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Optical lattices are periodic potentials created by the interaction of atoms with a standing wave laser field, capable of trapping atoms in the wavelength-sized wells. [1]. An interesting question immediately arises: Does localization in individual wells prevent atoms in an optical lattice from colliding with one another? Since collisions are an important loss mechanism in traps, especially those for metastable atoms, such an apparently simple collision suppression mechanism is of great interest. It is not obvious, however, that spatial localization will reduce the rate of collisions; one might imagine that atoms with energies too high to be bound or those that hop from site to site [2] will be "guided" by the periodic potential towards bound atoms, enhancing the collision rate. We show in this Letter that both enhancement and suppression can in fact occur. In a far-off-resonant lattice of metastable xenon, we study how the effect of the lattice changes from collisional enhancement to suppression as the atoms in the lattice thermalize and localize in the wells. We take care to account for the modification of the collision cross section induced by excited state population [3–5] but unrelated to the lattice dynamics. This study of collisions provides a probe of the transport characteristics of the lattice; we derive an estimate of the "hopping" rate between potential wells (lattice sites). We note that a related study in metastable argon and krypton has recently been carried out in Tokyo [6].

Penning ionizing collisions between metastable xenon atoms used in this work produce copious numbers of ions that may be detected with high temporal resolution. The apparatus to trap and cool metastable xenon and to detect collisions has been described previously [7]. In addition, a microchannel plate (MCP) 15 cm below the trap region allows us to detect metastable atoms after release from the lattice; the temperature may be readily extracted from the width of the arrival-time distribution. Our lattice is created by four travelling waves, as proposed in [8]. As in [9,10], we use two pairs of beams propagating in planes perpendicular to each other, with a 90° angle between the beams of each pair; the pairs have orthogonal linear polarizations. We use light from a Ti:Sapph laser tuned below the $6s[3/2]_2 \rightarrow 6p[5/2]_3$ transition at $\lambda = 882\,\mathrm{nm}$. The maximum light shift potential U_0 is given by $U_0 = (14/15)\{(I/I_0)/(\mid \delta \mid /\Gamma)\}\hbar\Gamma$ in the large detuning, low-saturation limit valid for all of the work to be described; $\Gamma = 2\pi \times 5.22\,\mathrm{MHz}$ is the natural linewidth, δ is the detuning from atomic resonance, I is the intensity of a single travelling laser wave, and the saturation intensity $I_0 = 0.9\,\mathrm{mW/cm^2}$. The lattice constants are $a_z = \lambda/2\sqrt{2}$ and $a_{x,y} = \lambda/\sqrt{2}$. Atoms in our red-detuned ($\delta < 0$) lattice cool and accumulate in regions where the light intensity is a maximum; for our geometry and polarizations the intensity in the bottom of a well is $8I$. The large detunings (of order 10 GHz) of interest to us require high laser intensity to produce a reasonable U_0; we accomplish this with relatively small ($w_0 = 1.5\,\mathrm{mm}$) beam waists. Light for our lattice is spatially filtered and split into two beams; each beam then passes through the vacuum chamber and after emerging is "recycled" by being sent through a second time. We use trap loss caused by detuning the laser to the open $6s[3/2]_2 \rightarrow 6p[5/2]_2$ transition to aid in alignment.

To load the lattice atoms are collected in a magneto-optical trap and subsequently cooled in optical molasses. This yields a cloud of $N \simeq 10^6$ atoms at a density of $n \simeq 3 \times 10^{10}\,\mathrm{cm^{-3}}$ and a temperature of $\sim 6\,\mu\mathrm{K}$. A short time ($200\,\mu s$) after all light has been extinguished, we switch on the light creating the optical lattice. When the lattice is loaded, the fraction of available sites occupied is on the order of 10^{-3}. After being left on for a period of variable duration, the lattice light is extinguished. Ionizing collisions between atoms are monitored the entire time. Since individual atomic velocities are uncorrelated, the sample becomes disordered a short time after the lattice is switched off. The macroscopic density, however, is unchanged on this time scale, so any abrupt change in the collision rate must be due only to the effects of the lattice light; this includes those related to the optical potential and the effect of excited state population on the collision rate.

Figure 1a shows the time-of-flight distribution for atoms falling on the MCP following preparation in optical molasses. The effective temperature is $\sim 6\,\mu$K. Also shown is the distribution resulting when the molasses phase has been followed by a lattice phase of 100 ms. In this case the distribution is Gaussian, with a corresponding temperature of $\sim 15\,\mu$K. [11] The intensity of each lattice beam is $I = 5\,\mathrm{W/cm^2}$ and the detuning $\delta = -4800\Gamma$, giving a maximum photon scattering rate at the lattice sites of $7400\,\mathrm{s}^{-1}$ and corresponding saturation parameter $s \simeq 5 \times 10^{-4}$. Figure 1b shows the collision rate measured during the lattice phase and afterwards. The drop in the collision rate while the lattice is on reflects a reduction in density due to spatial diffusion and loss due to collisions, as well as localization of atoms in the lattice. After the lattice is switched off, the collision rate abruptly jumps up by a factor of two, reflecting collision suppression in the lattice. At this point the atoms follow ballistic trajectories, and the density and collision rate drop accordingly.

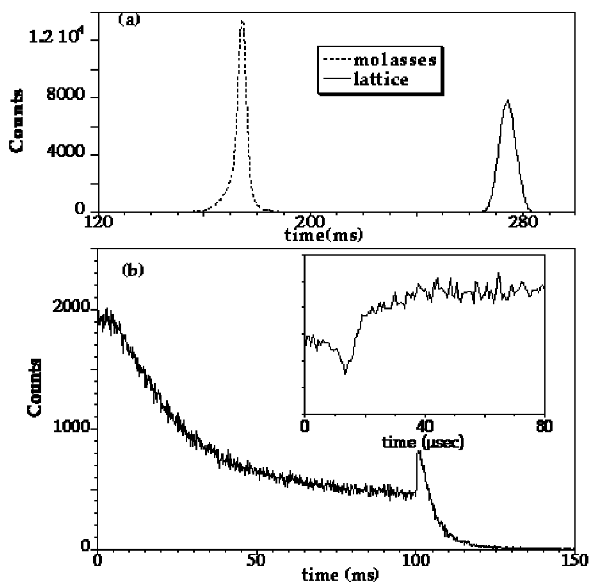

FIG. 1.
a. Time of flight distributions for atoms released from molasses and lattice. Extinction of the molasses defines the origin of time. The lattice laser detuning is $\delta = -4800\,\Gamma$, and the intensity in each beam is $I = 5\,\mathrm{W/cm^2}$.
b. Penning ionization detected during the lattice phase and afterwards. The data reflect an average of 50 cycles, and the width of each time bin is 164 μs. Inset: a high-resolution view of the transition from ordered to disordered atomic sample with an origin at 100 ms, averaged for 12,000 cycles.

We now focus attention on the jump in the collision rate occurring when the lattice is shut off. We examine the suppression factor $R_{\mathrm{lattice}}/R_{\mathrm{free}}$, the ratio of the collision rate in the lattice to that of the free atoms immediately after switchoff; Fig. 2 shows $R_{\mathrm{lattice}}/R_{\mathrm{free}}$ vs. lattice duration. It is clear that at short times the collision rate in the lattice is enhanced over that for free atoms, while at times longer than a time τ_c, in this case about 20 ms, the collision rate is suppressed in the lattice. Additional insight is gained by considering the corresponding lattice temperatures, also shown in Fig. 2. It is clear that the two curves have similar temporal dependences. We interpret this result as showing that collision suppression occurs only when sufficient cooling has taken place in the lattice that atoms are well localized in individual wells. Indeed, by making a number of scans like Fig. 2 at different detunings, we have found that the time τ_c required to observe collision suppression scales as δ^2. In steady state the collision rate is a factor of two lower in the lattice than that for free atoms at the same density.

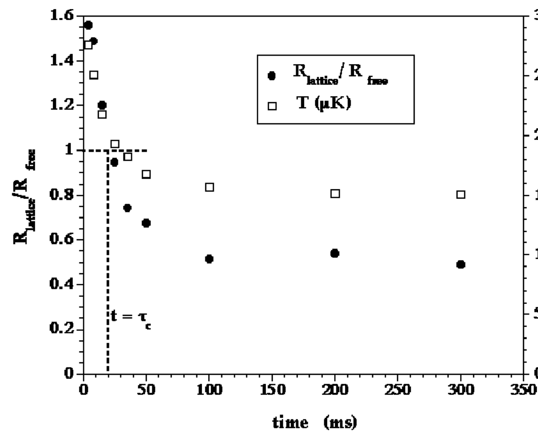

FIG. 2.
Solid circles: Comparison of collision rate in the lattice to that of free atoms as the lattice thermalizes. The rates are equal at $\tau_c \simeq 20$ ms.
Open boxes: Lattice temperature. The laser parameters are the same as those of Fig. 1.

For times less than τ_c, the collision rate in the lattice is greater than that for free atoms. We interpret this as resulting from a higher effective density in the lattice, as atoms with low energies immediately after loading will be excluded from areas where the potential is high; alternatively put, the effect of the potential will be to localize atomic trajectories near potential minima rather than allow them to be uniformly distributed.

It is important to verify, even at these large detunings, that the collision enhancement we observe is due to localization and not simply due to the well-known enhancement of collision rates that occurs in the presence of red-detuned light [3–5]. We do this in two ways. First, we measure the collision enhancement caused by a travelling wave in which there can be no induced localization. In practice we take a series of measurements with travelling waves of detunings from 1 to 7 GHz; since the enhancement is very small at large detunings we extrapolate to the 24 GHz detuning used for the data of Fig. 2. In this way we infer that a travelling wave of an intensity $8\,I$, corresponding to the maximum local intensity in the lattice, would account for at most 20% of the collision enhancement observed. As a second check, we raised the temperature of the atoms with which the lattice was loaded by shortening the molasses phase. The results are shown in Fig. 3, where it is clear that the collision enhancement diminishes as the loading temperature is raised, vanishing for a load temperature of $\sim 70\,\mu$K. At this temperature the atoms moved only about $12\,\mu$m during the $200\,\mu$s before the lattice was switched on, a distance much less than the size of our lattice beams.

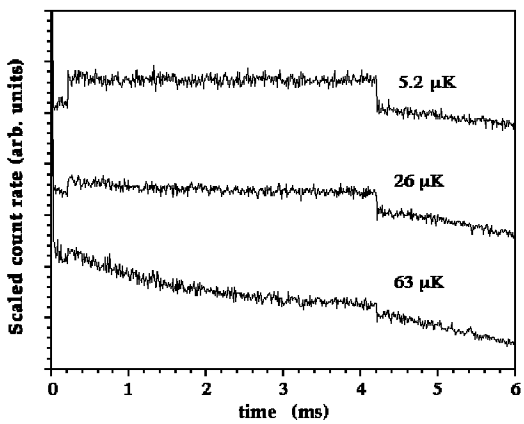

FIG. 3.
Collision rate enhancement when the lattice is switched on, for three different load temperatures. The data have been scaled to give the same rate after the lattice is switched off, and offset for clarity. The laser parameters are the same as those of Fig. 1.

We now study how the collision rate for a lattice in steady state varies with the laser detuning. Fig. 4 shows the ratio $R_{\rm lattice}/R_{\rm free}$ at lattice switchoff vs. δ for a constant intensity; in all cases the lattice duration was sufficient to assure that steady state had been achieved. The collision suppression is best for large detunings; however, it is impractical to detune further than about $5000\,\Gamma$ as the photon scattering rate becomes so low that in the time required for thermalization too many atoms are lost to collisions with background gas. We are thus unable to say if we could achieve better collision suppression by detuning further, although the data suggest that this is unlikely. At a detuning of about 1900Γ, it is seen that the lattice collision rate is the same as that in the absence of optical potential. However, at this detuning, the collision enhancement caused by excited state population is significant. In fact, a travelling wave with intensity $8\,I$, corresponding to that at the bottom of a potential well, would more than double the collision rate relative to that in the absence of light. In this spirit, it seems appropriate to consider the ratio $R_{\rm lattice}/R'_{\rm free}$, where $R'_{\rm free}$ is the collision rate induced by a travelling wave of intensity $8\,I$. This is also shown in Fig. 4. Viewed in this light, one sees that in steady state the lattice *always* suppresses collisions by at least a factor of two, and the suppression becomes more and more effective close to resonance.

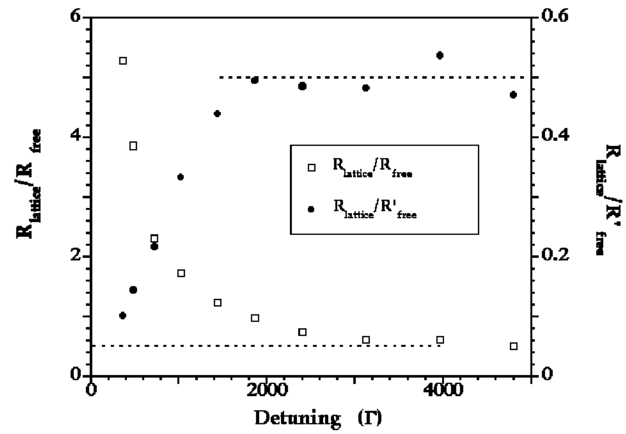

FIG. 4.
Open boxes: $R_{\rm lattice}/R_{\rm free}$ vs. detuning. Note that $R_{\rm lattice}/R_{\rm free} \to 0.5$ at large detuning.
Solid circles: $R_{\rm lattice}/R'_{\rm free}$, collision suppression where $R'_{\rm free}$ is the inferred collision rate in the presence of a travelling wave with an intensity $8I$. The intensity was the same as in Fig. 1, and the lattice duration was sufficient to assure equilibration at each detuning.

We now consider the dynamics in steady state and at the moment the lattice light is shut off; for simplicity we assume the excited-state population is negligible. We expect that in steady state the collision rate $R_{\rm lattice}$ is the product of the number $\mathcal{N}^{(2)}$ of sites containing two atoms and the rate κ at which two atoms in the same site collide. The number $\mathcal{N}^{(2)}$ is determined by an equilibrium between the loss rate κ and the "hopping" rate $\gamma_{\rm h}$ at which atoms change sites. The annihilation rate κ can be estimated using the measured rate constant $\beta = 6\times 10^{-11}\,{\rm cm^3\,s^{-1}}$ [3] and the lattice localization for atoms in a similar lattice measured in [10] for cesium, $x_{\rm rms} = \lambda/7.3$ and $z_{\rm rms} = \lambda/12$, giving a rate of $\kappa = 1400\,{\rm s}^{-1}$. In the limit that the "hopping" rate is small compared to the annihilation rate κ, a simple calculation gives $\mathcal{N}^{(2)} = nNv\gamma_{\rm h}/\kappa$, where N is the total number of atoms, n is the density, and v is the volume of a unit cell (the product nv is the probability of a single site being occupied). In this limit the total collision rate is $R_{\rm lattice} = nNv\gamma_{\rm h}$, independent of κ. Collisions in the lattice are thus solely a measure of transport, independent of the collision cross section. The collision rate for free atoms [12] is $R_{\rm free} = nN\beta/2$. We may thus extract the "hopping" rate as $\gamma_{\rm h} = (R_{\rm lattice}/R_{\rm free})\beta/2v$. Since we find that $R_{\rm lattice} \simeq R_{\rm free}/2$ at large δ, in steady state, we infer $\gamma_{\rm h} = 125\,s^{-1}$, or a mean time per atom between hops of 8 ms. One might expect that γ_h is proportional to the optical pumping rate. The fact that Fig. 4 suggests that the suppression saturates at large δ implies that in fact the "hopping" rate is not due to optical pumping. Other mechanisms, independent of δ, must be responsible for transport between sites; these might include fundamental effects such as tunneling, as well as technical ones such as mirror vibrations. This picture clarifies why the lattice appears more effective at suppression at small detunings when compared to a travelling wave: free particles scatter more often when they have large cross sections (resonant enhancement at small detuning), while the rate of scattering in a lattice is limited by the "hopping" rate between sites and is not increased by a larger cross section [13].

When the lattice is shut off, the distribution of positions should have two characteristic features; a small number ($\mathcal{N}^{(2)}$) of pairs of atoms separated by less than $x_{\rm rms} = \lambda/7.3$ and a deficit of pairs separated by $a_{\rm x,y}/2$ [14]. We can in fact see this manifest in a high-resolution look at the jump. At very short times, the only collisions possible are those between atoms that were in the same well at the time of release. We can estimate the decay rate of these collisions by considering the decrease in the density $n(t)$ in a single well as the distribution spreads in time due to ballistic motion. The characteristic time over which $n(t)$ falls off is given by $\tau_{\rm fall} \simeq x_{\rm rms}/v_0$, where v_0 is the mean speed of an atom. Taking the value $v_0 = 3$ cm/s appropriate for $15\,\mu K$, we expect the collision signal to initially drop for a time of order $\tau_{\rm fall} \simeq 3\,\mu s$. Similarly,the signal should rise again when the density distributions from neighboring wells start to overlap; the characteristic time here is $\tau_{\rm rise} \simeq a_{\rm x,y}/v_0 = 11\,\mu s$. This behavior is strikingly shown in the inset of Fig. 1b. We attribute the $\sim 10\,\mu s$ delay before the signal starts to drop to the time of flight to our ion detector.

As a final note, we have found that effective collision suppression requires careful attention paid to beam quality, alignment, and polarization. With the setup described, we find signals such as shown in Fig. 1b routinely. If the beams are not spatially filtered, however, collision suppression is rarely observed. The collision signal is similarly quite sensitive to beam polarization. In contrast, other lattice characteristics, such as the temperature, are far less sensitive to these parameters.

In conclusion, we have demonstrated that collision rates are enhanced in an optical lattice when it is far from equilibrium and suppressed in steady state. We have accounted for the effect of near-resonant light and interpreted our results accordingly. At best, we are able to suppress the collision rate by a factor of two from its value in the absence of laser light. It would be interesting to know if this is a fundamental limit or a consequence of imperfections in our lattice such as vibrations, laser amplitude noise, etc. We are currently attempting to predict the steady-state collision rate through Monte Carlo simulations. We are hopeful that collisions will be a useful diagnostic for future work concerning spatial diffusion and quantum transport in optical lattices far from resonance.

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[1] P. S. Jessen, I. H. Deutsch, Adv. At. Mol. Opt. Phys. **37**, 95 (1996), and references therein.

[2] C. Jurczak, B. Desruelle, K. Sengstock, J.-Y. Courtois, C. I. Westbrook, and A. Aspect, Phys. Rev. Lett. **77**, 1727 (1996).

[3] M. Walhout, U. Sterr, C. Orzel, M. Hoogerland, and S. L. Rolston, Phys. Rev. Lett. **74**, 506 (1995) .

[4] F. Bardou, O. Emile, J.-M. Courty, C. I. Westbrook, and A. Aspect, Europhys. Lett. **20**, 681 (1992) .

[5] P. Julienne, A. Smith, and K. Burnett, Adv. At. Mol. Opt. Phys. **30**, 141 (1993) .

[6] H. Kunugita, T. Ido, and F. Shimizu, to be published in Phys. Rev. Lett.

[7] M. Walhout, H. J. L. Megens, A. Witte, and S. L. Rolston, Phys. Rev. A. **55**, R3987 (1997) .

[8] G. Grynberg, B. Lounis, P. Verkerk, J.-Y. Courtois, and C. Salomon, Phys. Rev. Lett. **70**, 2249 (1993).

[9] A. Kastberg, W. D. Phillips, S. L. Rolston, R. J. C. Spreeuw, and P. S. Jessen, Phys. Rev. Lett. **74**, 1542 (1995) .

[10] M. Gatzke, G. Birkl, P. S. Jessen, A. Kastberg, S. L. Rolston, and W. D. Phillips, Phys. Rev. A. **55**, R3987 (1997) .

[11] This temperature is surprisingly low in light of the previously measured proportionality between T and U_0 [10] in cesium, and merits further investigation, which is beyond the scope of this paper.

[12] Here we make the simplifying assumption that the macroscopic density is uniform since a macroscopic density distribution would drop out in the ratio.

[13] Although the hopping rate should increase due to optical pumping at small δ, it will have the same dependence (δ^{-2}) as the increased collision cross section. From the data it is evident that the increase in cross section dominates the increase in hopping rate.

[14] Here we choose the x direction for simplicity; a more detailed calculation would incorporate the anisotropic character of the lattice.