Paramagnetism in a Cesium Optical Lattice

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We report the observation of paramagnetic behavior of an optical lattice operating on the $F_g = 4 \rightarrow F_e = 5$ resonance of cesium. This paramagnetism results from the transfer of population between optical potential wells associated with different magnetic sublevels. The populations are deduced from the amplitudes of stimulated Raman resonances observed in the transmission spectra of probe beams with σ^+ and σ^- circular polarizations.

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There has recently been considerable activity in the field of optical lattices [1–6]. Such a lattice is obtained at the intersection of several laser beams which give rise to a light field with spatially periodic polarization and intensity. The consequent spatial modulation of the light shifts in the ground state of an atom having a transition nearly resonant with the light field leads to the formation of a lattice of potential wells in which atoms are efficiently trapped. The occupation time of an atom in a given potential well is significantly increased when the light polarization at the potential minimum is circular. In this case an atom exactly localized at the bottom of the potential well is optically pumped into ground-state Zeeman sublevels of magnetic quantum number $m_g = \pm F_g$ (F_g being the angular momentum of the ground state). The leakage to other Zeeman sublevels, which involves photons of different polarization, results from the spatial extent of the atomic wave function [7].

Lattices studied in experiments to date have either a ferromagnetic [3,6] or an antiferromagnetic structure [4,5]. In the ferromagnetic lattices all the trapping sites correspond to the same circular polarization and the trapped atoms therefore have the same spin orientation. By contrast, in the case of an antiferromagnetic lattice, adjacent well sites are associated with opposite circular polarizations of the light field and atoms trapped at these sites consequently have oppositely oriented spins. The filling factor of lattices currently observed in experiments is of the order of 10^{-2}, the atoms being randomly distributed among the potential minima with an equal probability, in an antiferromagnetic lattice, of occupying a σ^+ or a σ^- potential well.

An interesting question to ask is how these occupation probabilities evolve in the presence of a longitudinal magnetic field. Because of the Zeeman effect, there will be an opposite shift for the potential wells corresponding to $m_g = F_g$ and $m_g = -F_g$. As a result, one might expect, from usual statistical physics arguments, a transfer of atoms towards the wells having the lowest potential energy, with the consequent creation of a net macroscopic magnetization of the lattice. We show that this behavior is observed in an experiment performed with cesium atoms, despite the fact that the atoms are not in equilibrium with a thermal bath and that it is possible to extract a spin temperature from our data.

We show that the usual band model [8] applied to the case of a ground state having angular momentum $F_g = 1$ gives predictions in qualitative agreement with the experimental results but demonstrates that such behavior does not occur in the system often used for model lattice calculations, in which the ground state has angular momentum $F_g = 1/2$. In the experiment we compare the measured spin temperature with the kinetic temperature measured under the same conditions. Finally, we describe an experiment employing a pulsed magnetic field which yields information on the time evolution of the population in the σ^+ and σ^- potential wells.

The experiment is carried out with a four-beam lattice [3] loaded with atoms from a magneto-optical trap, identical to the one described in [5]. This lattice corresponds to a simple 3D generalization of the well-known 1D lin⊥lin configuration. It consists of two y-polarized beams propagating in the xOz plane each at an angle of $\theta_x = 15°$ to the symmetry (Oz) axis and two x-polarized beams propagating in the yOz plane at an angle of $\theta_y = 25°$ to Oz [Fig. 1(a)]. The lattice beams have a frequency detuning Δ of 5Γ to 10Γ (Γ is the natural width of the excited state) to the red side of the $F_g = 4 \rightarrow F_e = 5$ component of the $D2$ resonance of cesium. The intensity of each beam is typically 1 mW cm^{-2} to 10 mW cm^{-2}. As shown in [5,9], such a configuration generates a light field which can be thought of as being composed of two interpenetrating orthorhombic lattices of points at which the light field is circularly polarized, the two lattices corresponding to sites at which the light polarization is either σ^+ or σ^-. The maximum light shift of the lowest lying cesium ground-state sublevel occurs at sites of circular polarization, where it corresponds to the $m_g = 4$ or $m_g = -4$ Zeeman substate. The spatial dependence of the potential energy of this sublevel is as illustrated in Fig. 1(b), which shows the potential energy variation along the Oz axis. In the magnetic field-free case the potential energy minima associated with points of opposite circular polarization have the same energy and the populations in the

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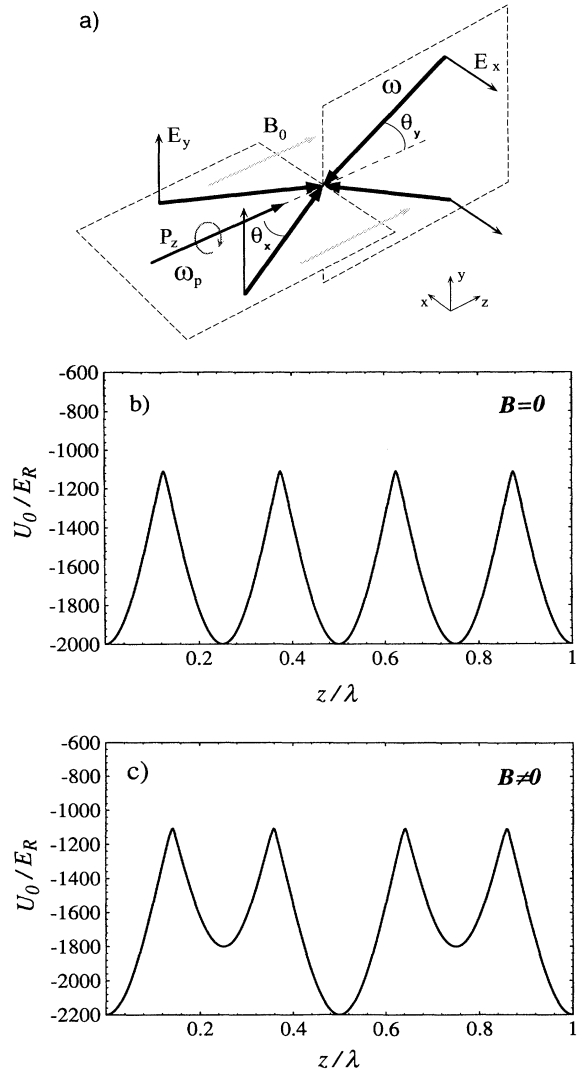

FIG. 1. (a) Field configuration of the light-induced lattice. Energy of the most light-shifted sublevel as a function of position on the symmetry axis for a lattice operating on a $F_g = 4 \rightarrow F_e = 5$ transition for the case of (b) $B_0 = 0$ and (c) $B_0 = 200$ mG. $\lambda_{\parallel}$ is the spatial period of the lattice along Oz.

σ^+ and σ^- wells are equal. When a static longitudinal magnetic field B_0 is applied along the Oz axis, the $m_g = 4$ and $m_g = -4$ sublevels experience Zeeman energy shifts $\mu_B B_0$ equal in magnitude but opposite in sign. As a result, the potential depths are no longer equal at sites of σ^+ and σ^- polarization [Fig. 1(c)].

We have studied the population in the wells at sites of σ^+ and σ^- light polarization using stimulated Raman spectroscopy. A weak circularly polarized probe beam P_z, of which the frequency is tuned around that of the lattice-inducing waves, propagates along the Oz axis [Fig. 1(a)], the transmitted intensity being monitored by a photodiode. These spectra exhibit Raman resonances corresponding to a unit change in the vibrational quantum number characterizing the bound atomic motion along the Oz direction of atoms trapped at individual well sites [3]. These resonances occur for a detuning δ of the probe wave from the lattice waves equal to the vibration frequency Ω_z. Since the populations of the vibrational states decrease with increasing vibrational quantum number, the resonance appears as a gain of the probe wave for $\delta = \Omega_z$ and absorption for $\delta = -\Omega_z$. Because the Clebsch-Gordan coefficient connecting $m_g = 4$ to $m_e = 3$ is small compared to that associated with the $m_g = 4$ to $m_e = 5$ transition, a $\sigma^{+(-)}$ polarized probe excites stimulated Raman transitions mainly with atoms trapped in a $\sigma^{+(-)}$ well of the lattice. By measuring the amplitude of the stimulated Raman resonances as a function of the probe polarization one can therefore infer the relative populations of the σ^+ and σ^- wells. As expected, and as shown in Fig. 2(a), for the case of $B_0 = 0$ the transmission spectra for opposite circular polarizations of the probe are the same. The amplitudes of

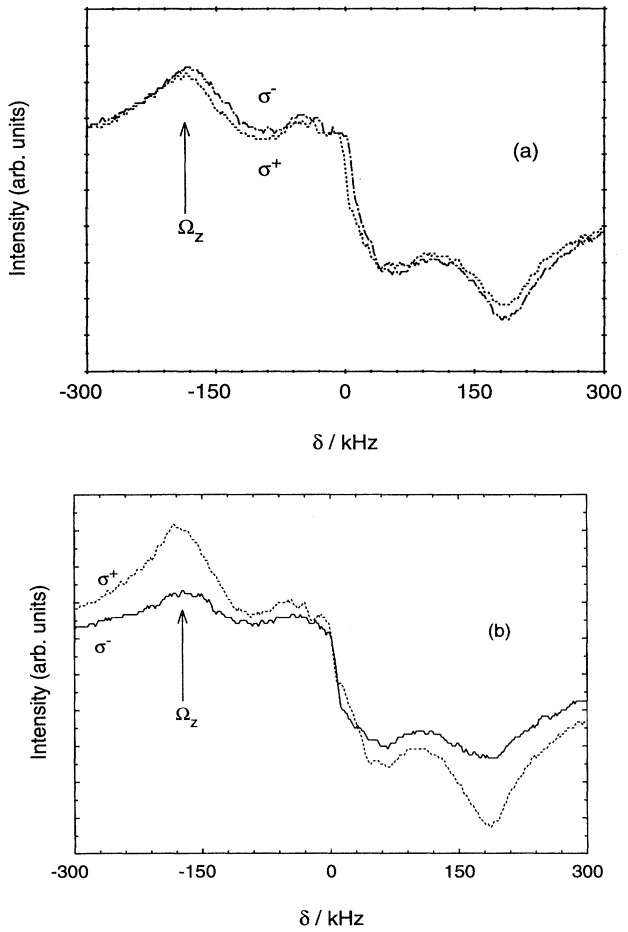

FIG. 2. Probe transmission spectra for σ^+ and σ^- circular polarizations of the probe as a function of the probe-lattice field detuning δ for the case of (a) $B_0 = 0$ and (b) $B_0 = 300$ mG.

the Raman peaks corresponding to σ^+ and σ^- probe polarizations are clearly different, however, for the spectra of Fig. 2(b) which were obtained by subjecting the lattice to a static longitudinal magnetic field, $B_0 = 300$ mG. This is a manifestation of the difference in population of the σ^+ and the σ^- potential wells. We also find that in the range of values of B_0 employed in this experiment, $B_0 < 0.4$ G, the position of the Raman resonances varies by less than 10%. We have plotted in Fig. 3(a) the ratio of the amplitudes of the Raman resonances, as found by subtracting the other components of the spectra of Fig. 2, versus B_0. The fitted curve is of the form $\exp -(2\mu_B B_0/k_B T_s)$ with $T_s = 40$ μK, the exponential form of the data suggesting the introduction of the phenomenological spin temperature T_s. Similar curves were obtained for several values of I/Δ, and we show in Fig. 3(b) the variation of T_s with U_0/E_R where

$$U_0 = (\hbar\Omega_z)^2/E_R(\cos\theta_x + \cos\theta_y)^2$$

is the light shift amplitude for $B_0 = 0$ and E_R is the one-photon recoil energy ($E_R/h = 2.2$ kHz for cesium). In plotting these data we obtain the abscissa from values of Ω_z deduced from the positions of the Raman resonances

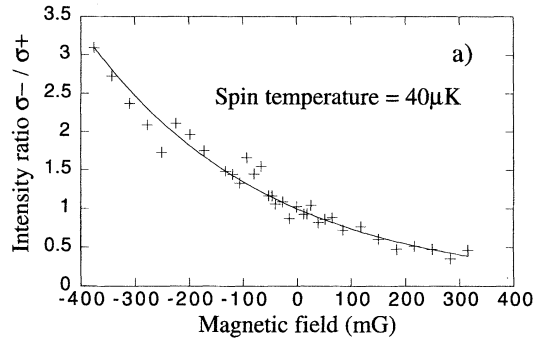

FIG. 3. (a) Plot of the ratio of the amplitudes of stimulated Raman transitions excited with σ^+ and σ^- polarizations of the probe field as a function of the amplitude, B_0, of the longitudinal magnetic field. The exponential form of the curve suggests the introduction of a spin temperature for the lattice. (b) Variation of the measured spin temperature T_s and kinetic temperature T_k with U_0/E_R. Note that the absolute position of the kinetic temperature data is subject to an uncertainty of 10 μK owing to the limited precision of our determination of the lattice size.

in the probe transmission spectra. It is evident that in the range of U_0/E_R studied here T_s is a linear function of U_0/E_R. The atomic kinetic temperature (along the direction Oy) was measured for conditions corresponding to those of the above data by a time-of-flight technique. This temperature, which shows the expected linear variation with U_0/E_R is also shown in Fig. 3(b) [10].

We have performed a numerical calculation of the paramagnetic behavior and of the corresponding kinetic temperature for a model system of a one-dimensional lin⊥lin optical molasses. Following [8] we have solved the generalized Bloch equations (i.e., including the external degrees of freedom) for a $F_g = 1 \rightarrow F_e = 2$ transition in the presence of a magnetic field and calculated, as in [7], the probe transmission spectra [11]. We find that the calculated ratio of the amplitudes of the vibrational Raman spectra with different circular probe polarizations scales to a good approximation with the calculated ratio of the populations of the σ^+ and σ^- wells [12] and that this ratio varies with the magnetic field amplitude. The calculated variation of T_s, defined as in the experiment, is shown in Fig. 4. The linear variation with U_0/E_R is in good agreement with the experiment. The calculated kinetic temperature is also shown in Fig. 4. It is of the same order of magnitude as T_s but is not identical [13].

Interestingly, a theoretical analysis for a transition with a ground state with $F_g = 1/2$ reveals no paramagnetic behavior. The reason for this is that for $F_g = 1/2$ the ground-state eigenstates of the light shift Hamiltonian are precisely the Zeeman substates and are space independent [8]. A longitudinal magnetic field therefore oppositely displaces in energy the two potential curves, but does not alter their wave functions or, consequently, the transition rates between them. By contrast, for $F_g \geq 1$ the most light-shifted sublevel of the ground state is a space-dependent superposition of the various Zeeman

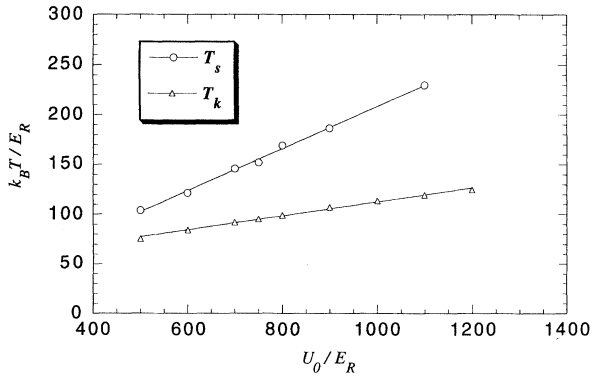

FIG. 4. Temperatures calculated as a function of U_0/E_R for a 1D optical lattice operating on a $F_g = 1 \rightarrow F_e = 2$ transition. T_s is the spin temperature defined from the ratio of vibrational Raman peak amplitudes with different circular probe polarizations, T_k the kinetic temperature and k_B Boltzmann's constant.

substates. In the presence of a static magnetic field the amplitudes of the Zeeman substates in this superposition are altered leading to a modification of the transition probabilities between the various light-shifted components of the ground state. In particular, depending on the majority circular polarization of a well, $\vec{B}_0$ is either parallel or antiparallel to the fictitious magnetic field associated with the light shifts. This breaks the symmetry in the admixtures of other sublevels into the most light-shifted state in the vicinity of sites of σ^+ and σ^- light polarization and leads to different transition rates for atoms trapped at "spin up" and "spin down" wells. The steady-state populations are consequently unequal.

Finally, we have studied the redistribution of atoms between the sets of σ^+ and σ^- wells in the time domain. For this purpose a pulsed longitudinal magnetic field was applied to the lattice for a period of approximately 10 ms, the field being switched on and off in an interval of less than 0.5 ms. The amplitude of the vibrational Raman peaks for a probe of σ^+ and σ^- polarizations was then monitored as a function of time by keeping the probe-lattice field detuning fixed at the vibration frequency Ω_z. We deduce from the data that the relaxation time for the populations is of the order of a few milliseconds. This corresponds to a transfer rate of order $\gamma_0(E_R/\hbar\Omega_z)$ where γ_0 is the optical pumping rate from the levels $|m_g| = F_g$ and $(E_R/\hbar\Omega_z)$ is the Lamb-Dicke factor [7].

In conclusion, we have demonstrated that the application of a longitudinal magnetic field to a sparsely populated antiferromagnetic optical lattice operating on a transition, for which $F_g \geq 1$, leads to an enhancement of the population of lattice sites associated with an atomic magnetic dipole moment parallel to the field direction at the expense of that of sites associated with a moment antiparallel to the field. This behavior, which is analogous to the reorientation of dipole moments that occurs in condensed matter subject to an external magnetic field, leads to the appearance of a macroscopic paramagnetic moment in the optical lattice. It is remarkable that, although the atoms in the optical lattice are not at thermal equilibrium, the observed population ratio agrees well with that expected from usual statistical arguments incorporating a well-defined spin temperature.

Possible extensions to this work include the study of paramagnetism in a "gray" lattice [14] operating on a $F_e = F_g$ or $F_e = F_g - 1$ transition. This is particularly interesting since in this system there are no potential wells in the absence of a magnetic field, a situation which should lead to the existence of much lower temperatures.

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[10] These temperatures are considerably higher than those observed recently by A. Kastberg *et al.* (to be published), since our lattice operates at a significantly larger value of U_0/E_R and because of the difference in geometry.

[11] We have also considered the case of a $F_g = 4 \rightarrow F_e = 5$ atomic transition. For this transition, however, our numerical model based on the secular approximation is only valid at much larger detunings. [The results are then dominated by resonant variations of the populations. See J.-Y. Courtois, Ph. D. thesis, Ecole Polytechnique, France, 1993)].

[12] The ratio of the amplitudes of the Raman resonances coincides within 20% with the calculated population ratio in the range of parameters employed in our calculation. The reason for the discrepancy between the Raman amplitudes and the population ratio is that the former depend on population differences between vibrational states in a given potential well and on matrix elements linking these levels. Both these factors are modified when a magnetic field is applied, which deforms slightly the shape of both σ^+ and σ^- wells.

[13] There is no rigorous way of defining the spin temperature for a system which is not at thermal equilibrium. By way of example, we have calculated the temperature derived from the magnetic susceptibility χ_H if one assumes the Curie law, $\chi_H \propto 1/T_s'$, to be valid. This temperature differs slightly from T_s but has a similar linear dependence on U_0/E_R. Other definitions that we have tried for a spin temperature give similar results.

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