Experimental Demonstration of the Optical Stern-Gerlach Effect

T. Sleator,[a] T. Pfau, V. Balykin, O. Carnal, and J. Mlynek
Fakultät für Physik, Universität Konstanz, Konstanz, Germany
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We report the observation of the splitting of an atomic beam by the optical Stern-Gerlach effect. A beam of metastable He atoms interacts with a nearly or exactly resonant laser field with a well-defined intensity gradient perpendicular to the atomic beam. The coherent splitting of the atomic beam is produced in the case of exact resonance. For the nonresonant case, a deflection of the atomic beam is observed. We have studied the splitting and deflection of the atomic beam as a function of laser detuning from resonance. Our results are in good agreement with theoretical predictions.

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Resonance light pressure on atoms is a field of intense research activity [1]. In particular, much work has been carried out on the dipole or gradient force. Such a force involves the interaction of an optical field gradient with the induced electric dipole moment of an atom. It was pointed out in 1975 [2] that the trajectory of a two-level atom interacting with an optical field gradient can under certain circumstances be split into two paths, each path containing atoms in one of the two orthogonal dressed states. Because of the state-selective deflection in a field gradient, this effect is often referred to as the Stern-Gerlach effect [3] in the optical domain ("optical Stern-Gerlach effect"). Although the theory of the optical Stern-Gerlach effect has been discussed extensively [2,4,5], it has not been observed so far [6].

The goal of our experiment was to demonstrate the optical Stern-Gerlach effect and to study its dependence on the laser frequency. In our experiments we used a collimated beam of metastable helium atoms interacting with a light field having a well-defined intensity gradient. This field was produced by bouncing a laser beam at a glancing angle off a glass surface, thereby producing a standing wave with period much larger than the width of the atomic beam (see inset of Fig. 1).

First, we briefly describe the theory of the optical Stern-Gerlach effect [2,4,5]. A two-level atom with transition frequency ω_0 interacts with a light field given by $\mathbf{E}(\mathbf{r},t)=\mathrm{Re}[\hat{\epsilon}E_0(\mathbf{r})\exp(i\omega t)]$, where $E_0(\mathbf{r})$ is the spatially varying electric field amplitude and $\hat{\epsilon}$ is the polarization vector. We model the field produced in our experiment by

$$E_0(\mathbf{r})=E_{0\,\max}\cos(k_x x)e^{ik_y y}e^{-z^2/w_0^2}. \quad (1)$$

This describes a standing wave with period $2\pi/k_x$ in the x direction, a traveling wave in the y direction, and a Gaussian beam profile with diameter w_0 in the z direction, which is the direction of the atomic beam. We assume that the atom enters the light field in the ground state $|g\rangle$ and that the interaction time of the atom with the field is much shorter than the atomic natural lifetime of the excited state $|e\rangle$. The velocity v of the atoms along the beam axis (z axis) is sufficiently large that the spatial dependence of $E_0(\mathbf{r})$ along $\hat{\mathbf{z}}$ can be replaced with the explicit time dependence $t=z/v$ in the atom's moving frame. We therefore replace the factor $\exp(-z^2/w_0^2)$ in Eq. (1) with $\exp(-t^2/t_0^2)$, where $t_0=w_0/v$. We ignore (for the moment) the y dependence of E_0, which is responsible for the Doppler shift and any momentum transfer along the y direction. With the above assumptions, the behavior of the atom in a light field can be described by a one-dimensional Schrödinger equation with the interaction Hamiltonian $H_I=-\mathbf{d}\cdot\mathbf{E}(x,t)$, where $\mathbf{d}$ is the atomic dipole-moment operator. With the rotating wave approximation, the Schrödinger equation in the interaction representation is

$$i\hbar\frac{\partial\psi_e}{\partial t}=-\frac{\hbar^2}{2m}\frac{\partial^2\psi_e}{\partial x^2}-\frac{\hbar\Delta}{2}\psi_e+\frac{\hbar\omega_1(x,t)}{2}\psi_g,$$
$$i\hbar\frac{\partial\psi_g}{\partial t}=-\frac{\hbar^2}{2m}\frac{\partial^2\psi_g}{\partial x^2}+\frac{\hbar\Delta}{2}\psi_g+\frac{\hbar\omega_1(x,t)}{2}\psi_e, \quad (2)$$

where the total wave function is $|\psi\rangle=\psi_e|e\rangle+\psi_g|g\rangle$ and the spatially dependent Rabi frequency is $\omega_1(x,t)=\langle e|\mathbf{d}\cdot\hat{\epsilon}|g\rangle E_0(x,t)/\hbar$ and the detuning $\Delta=\omega_0-\omega$. Di-

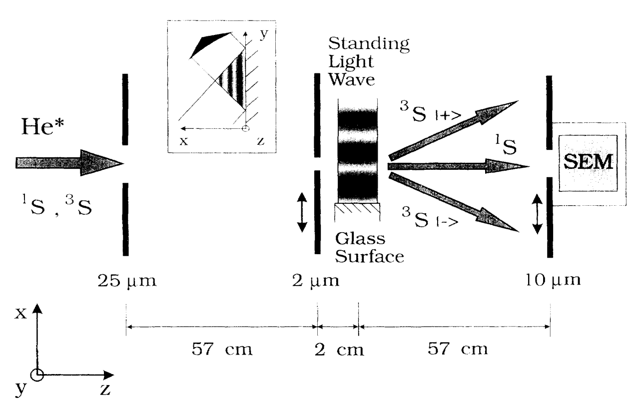

FIG. 1. Schematic diagram of the experimental setup as viewed from above. By the interaction with the standing light wave the atoms in the triplet state ^3S are split into the two eigenstates $|+\rangle$ and $|-\rangle$. Inset: View along the atomic beam axis of the optical standing wave.

agonalizing the interaction Hamiltonian yields two time-dependent eigenvectors,

$$|+\rangle=\sin(\tfrac{1}{2}\theta)|g\rangle+\cos(\tfrac{1}{2}\theta)|e\rangle,$$
$$|-\rangle=\cos(\tfrac{1}{2}\theta)|g\rangle-\sin(\tfrac{1}{2}\theta)|e\rangle, \quad (3)$$

with

$$\cos\theta(x,t)=\Delta/[\Delta^2+\omega_1^2(x,t)]^{1/2}$$

and

$$\sin\theta(x,t)=\omega_1(x,t)/[\Delta^2+\omega_1^2(x,t)]^{1/2}.$$

The corresponding eigenvalues are

$$U_\pm(x,t)=\pm(\hbar/2)[\Delta^2+\omega_1^2(x,t)]^{1/2}. \quad (4)$$

The behavior of the atomic center of mass depends on the internal state of the atom as it traverses the field, which in turn depends strongly on the detuning Δ. We consider the following three cases.

(i) When $\Delta=0$, the eigenstates $|+\rangle=(|g\rangle+|e\rangle)/\sqrt{2}$ and $|-\rangle=(|g\rangle-|e\rangle)/\sqrt{2}$ in Eq. (3) are time independent and Eqs. (2) can be decoupled by writing $|\psi\rangle=\psi_+|+\rangle+\psi_-|-\rangle$. The states ψ_+ and ψ_- propagate independently of one another, and experience potentials $\pm\hbar\omega_1(x,t)/2$ equal in magnitude but opposite in sign. A beam of atoms entering in the ground state $|g\rangle=(|+\rangle+|-\rangle)/\sqrt{2}$ will split into two distinct beams in the presence of a gradient in ω_1. It is this splitting that is referred to as the optical Stern-Gerlach effect. The momentum transfer to one atom is $\Delta p_\pm=\pm(\hbar/2)\int\nabla\omega_1(x,t)dt$, where x represents the position where the atom enters the standing wave. We have assumed that the deflection of the atoms is sufficiently small that their transverse displacement during the interaction time is much smaller than the standing-wave period. This condition is strongly satisfied in our experiments.

(ii) If the magnitude of the detuning $|\Delta|$ is much larger than a critical value Δ_c then the atom, which before entering the field is in state $|-\rangle$ if $\Delta>0$ or $|+\rangle$ if $\Delta<0$, will remain in this initial eigenstate throughout the interaction with the field, due to adiabatic following. The value of $\Delta_c/2\pi$ depends on the rate that the optical field turns on, and for our experimental conditions was about 30 MHz. Again, Eqs. (2) can be decoupled by the substitution $|\psi\rangle=\psi_+|+\rangle+\psi_-|-\rangle$. The atom, being in either state $|+\rangle$ or $|-\rangle$, and not in a superposition, sees a unique potential $(\hbar\Delta/2)[1+(\omega_1/\Delta)^2]^{1/2}$ and is therefore simply deflected.

(iii) When $0<|\Delta|<\Delta_c$, on the other hand, the situation is considerably more complicated. The atom, which before entering the laser field is in either state $|-\rangle$ if $\Delta>0$ or $|+\rangle$ if $\Delta<0$, does not remain in this eigenstate, but has the possibility to undergo transitions to the other eigenstate as it enters the laser field because of nonadiabatic coupling. Therefore, after entering the field, the atom is in a superposition of the eigenstates $|+\rangle$ and $|-\rangle$. Once the value of ω_1 is much greater than $|\Delta|$, there are no more transitions between $|+\rangle$ and $|-\rangle$, and the populations of these states remain fixed with ψ_+ and ψ_- being deflected in opposite directions according to the potential in Eq. (4). For nonzero values of Δ, one expects two distinct peaks with different intensities.

The experiments were carried out in an atomic beam machine [7] designed for metastable rare gas atoms. A supersonic expansion nozzle at room temperature produced a beam of He atoms, which were then excited into a metastable state by copropagating electrons at an energy of about 31 eV. Both singlet (2^1S_0) and triplet (2^3S_1) metastable states were produced. The result was a beam of metastable helium atoms (He*) with a velocity $v\simeq1760$ m/s and relative velocity spread $\Delta v/v\approx0.05$ full width at half maximum. As shown in Fig. 1, the atomic beam was collimated with a pair of slits: the first 25 μm wide, and the second 2 μm wide placed 2 cm upstream from the light field. The horizontal (x) position of the 2-μm slit could be adjusted by a piezo translation stage allowing us to set the position of the atomic beam in the light field. The horizontal deflection of the atomic beam was measured by scanning a detector behind a 10-μm-wide slit. The detector, a secondary electron multiplier, is sensitive to both metastable states but not to ground-state atoms and had a background count rate of roughly 6 counts/min.

The triplet He* atoms interact with light at 1.083 μm through the 2^3S_1 to 2^3P_2 transition. This light was produced by a single-mode Ti-sapphire ring laser (Coherent 899-21) pumped with 27 W from an Ar^+ laser. The laser frequency was locked by saturated absorption techniques to the atomic transition in a dc helium discharge, and could be adjusted by changing the value of an applied magnetic field. The laser frequency jitter was less than 1 MHz.

The laser output first passed through an intensity stabilizer and was then brought into the beam machine via a single-mode optical fiber. After leaving the fiber output coupler, the light with the typical power of 8 mW was focused by two cylindrical lenses and reflected with grazing incidence off of a glass surface, producing a standing wave with a period of about 15 μm (inset to Fig. 1). This surface was aligned parallel both to the height of the 2-μm slit to better than 10^{-4} rad and to the atomic beam axis to about 3×10^{-3} rad. The minimum laser beam diameter measured along the atomic beam direction was $w_0=39$ μm and the minimum diameter in the x direction was 140 μm. The interaction time between the atoms and light was roughly $2w_0/v=44$ ns, significantly less than the 2^3P_2 state natural lifetime of 100 ns. We estimate the Doppler spread in $\Delta/2\pi$ due to the vertical velocity spread and laser beam divergence to be about ±5 MHz for our experimental conditions.

No optical pumping was performed, so that the 2^3S_1 metastable state sublevels were equally populated. For the linearly polarized light used in our experiments, the ratio of the two dipole matrix elements was $(4/3)^{1/2}$, resulting in a spread in deflection angles of about 15% of

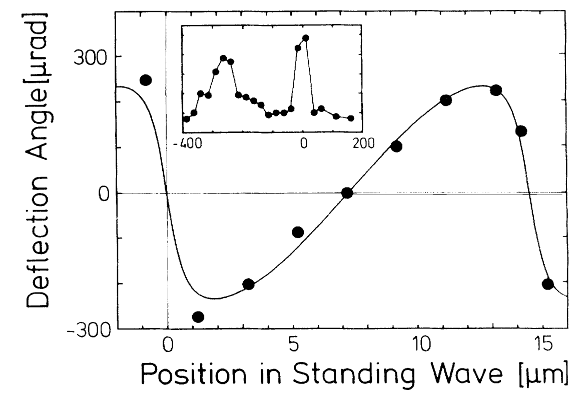

FIG. 2. Deflection of an atomic beam by a standing wave as a function of the position of the atomic beam in the standing wave. The detuning from resonance was $\Delta/2\pi = 160$ MHz. The laser power was about 24 mW. The solid line is a theoretical fit to the data. Position 0 on the horizontal scale was arbitrarily chosen to be at a node. Inset: Atomic intensity profile at the detector for the atomic beam at a position of -11 μm in the standing wave. The peak at zero angle is due to the undeflected singlet-state atoms.

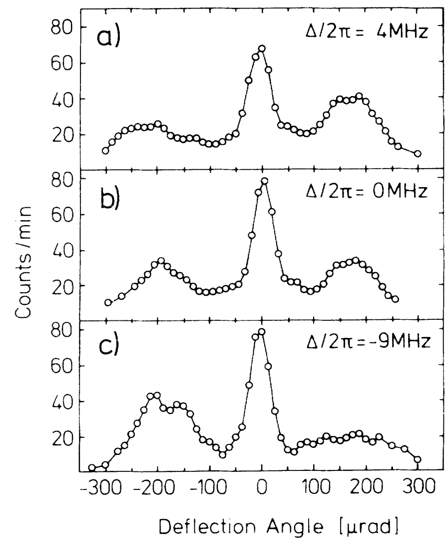

FIG. 3. Optical Stern-Gerlach effect. Atomic intensity profile for values of the laser detuning close to zero. $\Delta/2\pi = +4$ MHz (a), 0 MHz (b), and -9 MHz (c). The laser power was about 8 mW. The central peak at position zero is due to the undeflected singlet-state atoms.

the total deflection.

To characterize the optical potential and gradient, we first made a series of scans with a large laser detuning ($\Delta/2\pi = 160$ MHz) for various positions of the atomic beam in the standing wave. Our estimates of the critical value of detuning $\Delta_c/2\pi \sim 30$ MHz indicate that, for $\Delta/2\pi = 160$ MHz, the atomic beam should simply be deflected. This deflection is demonstrated in the inset of Fig. 2, which shows a plot of the atomic intensity profile at the detector. The narrow peak at 0 is produced by the undeflected atoms in the singlet metastable state. Notice that there is some broadening in the deflected part of the atomic beam. We attribute this broadening to arising primarily from the fact that the gradient of the field is not uniform across the width of the 2-μm slit, and that the metastable state sublevels ($J = 1$) of the unpolarized atomic beam have a different coupling with the light field. Figure 2 shows a plot of the measured deflection as a function of atomic beam position in the standing wave. The solid line shows a theoretical fit to these data obtained from the time integral of $\nabla U(x,t)$ with $\omega_1(x,t) = \omega_{1\,\max}\cos(k_x x)\exp(-t^2/t_0^2)$ in Eq. (4). With $\Delta/2\pi$ held fixed at 160 MHz, the value of $\omega_{1\,\max}/2\pi$ obtained from this fit is 1.4 GHz, which corresponds to a saturation parameter of 3×10^6, which is in reasonable agreement with the measured laser power. The data shown in Fig. 2 represent the first direct measurement of the dipole force and thus of the optical potential in a standing wave.

Figure 3 shows the atomic intensity profile at the detector for detunings less than 10 MHz. The atomic beam was at about position 11 μm in the standing wave (Fig. 2), which is near the position of maximum deflection. Here, we see that there are two distinct peaks deflected about 200 μrad from the central undeflected singlet peak, which corresponds to a change of transverse momentum Δp of roughly 4 times the photon recoil. It should be noticed, however, that the deflection is a continuous function of the field gradient, as discussed above. When the detuning was varied over about 20 MHz, the relative intensity of the two deflected peaks changed from being right weighted as in Fig. 3(a) ($\Delta/2\pi = +4$ MHz) to being left weighted as in Fig. 3(c) ($\Delta/2\pi = -9$ MHz), in agreement with the theory. Since it was difficult to determine the absolute frequency of the laser beam to better than a few MHz, the detuning was determined by the relative frequency shift from the value resulting in equal intensities of the two deflected peaks. We estimate the uncertainty in relative frequency shifts for our experiment to be about 1 MHz. The two deflected peaks shown in Fig. 3 constitute a demonstration of the transverse optical Stern-Gerlach effect.

As we have discussed above, the variation in the relative intensity of the two deflected peaks with Δ [Figs. 3(a)-3(c)] is due to variations in the degree of adiabatic following that the atom undergoes as it enters the light field. To compare these variations with those predicted by theory, we have plotted in Fig. 4 the normalized difference in integrated peak intensities $P = (I_r - I_l)/(I_r + I_l)$ versus the laser detuning $\Delta/2\pi$; here I_r and I_l denote the intensities of atoms being deflected to the right and left, respectively. The solid line shows the result of a simulation in which we have integrated the Bloch equations of this problem to determine the populations of the state $|+\rangle$ and $|-\rangle$ after the atom has entered the field.

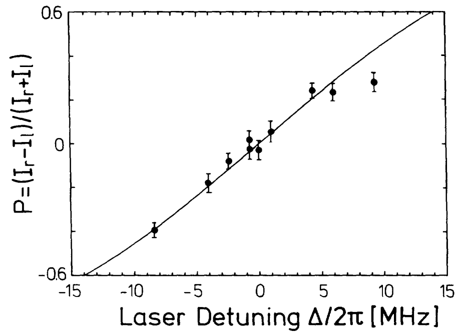

FIG. 4. Normalized difference in peak intensities $(I_r - I_l)/(I_r + I_l)$ vs laser detuning $\Delta/2\pi$. The solid line shows the result of a simulation based on integration of the Bloch equations.

In this simulation the atom interacts with a field of constant detuning Δ and amplitude of the form $\omega_1(t) = \tilde{\omega}_1 \exp(-t^2/t_0^2)$, where we have set $t_0 = 22$ ns and $\tilde{\omega}_1/2\pi = 1$ GHz from independent measurements. Although the only free parameter was the absolute frequency, the simulation is in good agreement with the data.

The theory of the optical Stern-Gerlach effect predicts that the two resulting beams should be completely coherent. A coherent beam splitter has potential applications, e.g., in atom interferometers [8]. To actually demonstrate the coherence of the two beams, it would be necessary to bring them together in an interferometer arrangement, and look for fringes.

For our experimental conditions, the effect of spontaneous emission is small, and we have therefore neglected it in our analysis. Further experiments with longer interaction times could be performed to test the effect of spontaneous emission [5]. The amount of splitting achieved in the current experiment could be increased either with a higher field intensity, e.g., by producing the standing wave in a resonator, or with a decreased standing-wave period, i.e., a larger field gradient.

Our experiments should be contrasted with previous experiments demonstrating the diffraction of an atomic beam by an optical standing wave [9]. In those experiments the atomic beam width was much larger than the standing-wave period and the atomic beam was split by the periodic potential into momentum states differing by multiples of $2\hbar k$. In our experiments, the splitting arises from the exactly resonant interaction of the atomic beam with an optical field gradient, and the splitting angle is a continuous function of this field gradient. In addition, the fact that the atomic beam width in our experiment (~ 2 μm) is much smaller than the period (~ 14 μm) of the standing wave allows us to distinguish effects involving a single position in the standing wave from those involving an average over many periods.

In conclusion, although the transverse optical Stern-Gerlach effect was discussed as early as 1975 [2], we believe that our experiments are the first demonstration of this effect. In addition, we have studied the near resonant deflection of a beam of atoms in a standing wave as a function of position in the standing wave. The results of both the deflection experiments and the optical Stern-Gerlach effect are in good agreement with the theory.

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[a]Present address: Department of Physics, New York University, New York, NY 10003.

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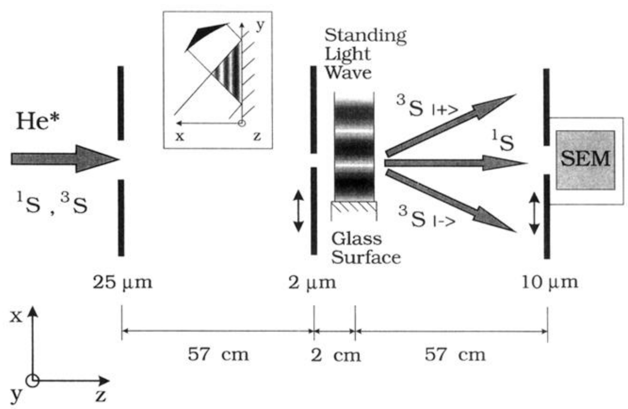

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