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We present a technique in which the total internal quantum state of an atom may be reconstructed via the measurement of the momentum transferred to an atom following its interaction with a near resonant traveling-wave laser beam. We present measurements that demonstrate the feasibility of the technique.

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The development of methods for completely determining the quantum state of an atom or cavity field [1] continues to be an important issue in atomic physics. For example, in the field of quantum optics, schemes have been recently proposed, based on the Stem-Gerlach effect, for completely determining the quantum state of an atom as a way of fully characterizing the quantized electromagnetic field of a cavity mode [2]. The reconstruction of an internal atomic state is important for goals as far reaching as reading the end state of a quantum gate operation [3] and teleportation of internal atomic states [4]. Walser *et al.* [2] describe a scheme whereby the field state of a cavity could be transferred to the magnetic sublevels of the internal state of an atom through the technique of adiabatic passage, thus converting the problem to one of determining a quantum state of an atom. Atom deflection has been suggested as a probe of the photon number in a cavity [5] and has also been used to measure the Mandel Q parameter of photon statistics for resonance fluorescence [6,7]. This technique provides a significant improvement over conventional photon counting schemes due to the poor efficiency of photon detection, which affects measurements of the Q parameter. In the field of electron-atom collision physics, the measurement of the atomic collision density matrix using coincidence and superelastic scattering methods depends on the complete determination of the quantum state of the atom [8].

The internal quantum state of an atom can be described by the density matrix formalism, which contains all the information about the quantum system. In principle, if one can measure all elements of the density matrix, then complete reconstruction of the quantum state of a system is possible. Atomic states are relatively insensitive to decoherence and can maintain an initial quantum state for long time scales compared to the characteristic times for preparation and detection, and as such they are frequently used in quantum computing proposals where insensitivity to decoherence is a requirement [9].

In this Rapid Communication, a method is presented for completely determining the density matrix of an atomic state based on laser induced deflection of the atom. The experiment is a realization of a suggestion put forward by Summy and co-workers [10–12] and represents the direct measurement of atomic density matrix elements for a state that has been created by some process. The motivation for this work is to develop an experimental tool that allows detailed information about the density matrix representing the state to be extracted. Using deflection with low laser powers, the technique relies on the difference in atomic absorption probabilities for individual optical hyperfine transitions that are not only dependent on the initial hyperfine substate populations, but also on the coherences between them. Hence, atoms in different states will be differentially deflected. It is shown that it is possible to reconstruct the internal state of the atom fully via the measurement of its center-of-mass motion after it has interacted with well defined polarized deflecting laser beams. It can be shown that the deflection of the atoms depends on the direction (relative to the defined quantization axis) and polarization of the laser [10]. It is this property that allows the required number of measurements to be achieved to fully characterize the density matrix.

It is worth noting here that a version of the Hanle effect in atomic ground states has been measured in which optically pumped atoms were deflected in the presence of a magnetic field [13]. A Hanle profile for the deflection of atoms was observed as the magnetic field was scanned through zero. This type of experiment yields information on the optical pumping time and indicates the presence of ground-state coherences within the ensemble of atoms. However, unlike the deflection method outlined here, there does not appear to be the number of experimental variables necessary to determine all density matrix elements.

For the purely optical method described here, it is possible to restrict the number of measurements if only a small part of the density matrix is of interest. A measurement is presented whereby one of the features of the density matrix is probed, namely, the orientation of the atom. The orientation is an important property of the atom in that it describes the amount of angular momentum transferred to the atom by processes such as optical pumping or collisions. The work presented here provides a proof in principle of being able to reconstruct the atomic state density matrix from measurements of the optical deflection force.

For a laser of single polarization mode k, incident on an atomic beam, the magnitude of the momentum imparted by the optical deflection force is given by [10–12]

$$p_k(t) = \hbar k \sum_g D_k^{gg}(t) \rho_{gg}^L(0), \tag{1}$$

where $\rho_{gg}^L(0)$ represents the initial density matrix elements

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of the lower state $|g\rangle$ of the transition excited by the deflecting laser. The density matrix has been defined in the laser excitation frame L, that is, the quantization axis (z axis) lies along the direction of the electric-field vector for linearly polarized light and along the direction of propagation for circularly polarized light. The x axis is chosen along the direction of propagation for linearly polarized light and in the direction of the atomic beam for circularly polarized radiation. The $D_k^{gg}(t)$ terms are called deflection parameters and depend on the hyperfine structure of the states involved in the laser transition and the optical pumping therein [10–12].

The aim is to determine the state of the atom prior to its deflection by a laser as this information will provide a description of the process that has prepared the atom. For example, if $|g\rangle$ is a state that has been excited by electron collision, then the atomic collision parameters can be determined by a complete analysis of the density matrix for that state [8]. In general, the laser deflection frame will differ from the relevant frame describing the preparation process, which is determined by the direction of an external field or some aspect of the geometry of the interaction. Transformation of the density matrix between the two frames is achieved by use of the rotation operator and rotating through the appropriate Euler angles [14].

To illustrate the method, we report the results of an experiment in which sodium atoms were first oriented by optical pumping and then subsequently deflected by laser light. We have previously reported a detailed study of optically pumping the sodium $D2$ transition using elliptically polarized light as an atomic state preparation technique [15]. Sodium atoms were prepared by elliptically polarized laser radiation exciting the $3\ ^2S_{1/2}(F=2)-3\ ^2P_{3/2}(F=3)$ hyperfine transition. The hyperfine energy levels associated with this transition are shown in Fig. 1. The atoms are then deflected using σ^- and σ^+ polarized radiation in turn. As the transition is between $F=2$ and $F=3$ states, the lower-state population differences between both the $m_F=1$ and -1 substates and the $m_F=2$ and -2 substates will contribute to the orientation of the atom. An orientation parameter P_o is defined as

$$P_o=(p_{\sigma^-}-p_{\sigma^+}), \tag{2}$$

where p_{σ^-} and p_{σ^+} are the deflection momenta for right- and left-hand circularly polarized light, respectively and are averaged over the interaction time.

Evaluating the momenta from Eq. (1) yields

$$P_o=\hbar k[(D^{-2-2}_{\sigma^+}-D^{22}_{\sigma^+})(\rho^L_{22}-\rho^L_{-2-2}) + (D^{-1-1}_{\sigma^+}-D^{11}_{\sigma^+})(\rho^L_{11}-\rho^L_{-1-1})], \tag{3}$$

where the symmetry relation $D^{gg}_{\sigma^-}=D^{-g-g}_{\sigma^+}$ has been used. Calculations show that the contribution from the $m_F=\pm1$ substates is an order of magnitude less than that from the $m_F=\pm2$ substates [15] and so the second term of Eq. (3) can be neglected.

A schematic of the experimental setup is presented in Fig. 2. A highly collimated, velocity-selected beam of sodium atoms passes through preparation and deflection laser interaction regions before traveling down a 1-m flight tube to a scannable hot wire detector. The atomic beam is velocity selected before the preparation region using two chopper wheels separated by 0.7 m. The beam has a longitudinal velocity width of about 10%. First, the atoms interact with a traveling wave, state preparation laser with arbitrary, but well defined, elliptical polarization. The polarization is set by the angle of a quarter-wave plate β with respect to the direction of the linear polarization of the laser radiation. For the

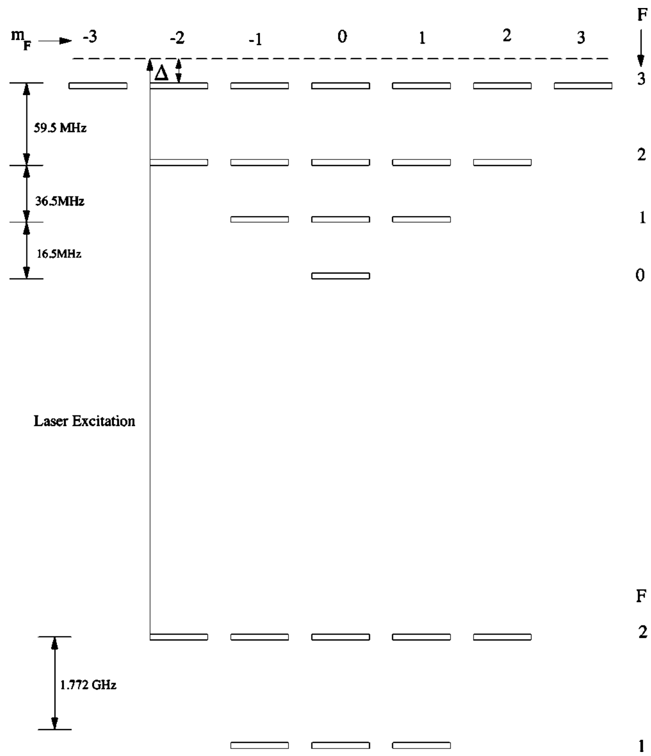

FIG. 1. Hyperfine energy level diagram for the sodium $D2$ transition.

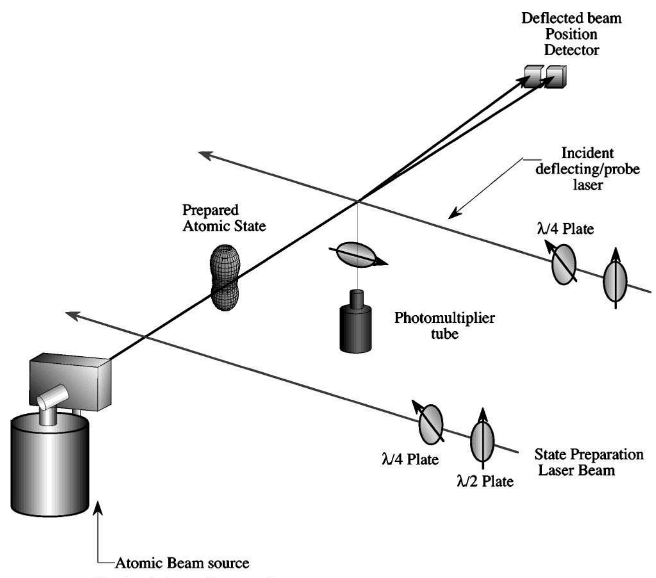

FIG. 2. Schematic of experimental setup.

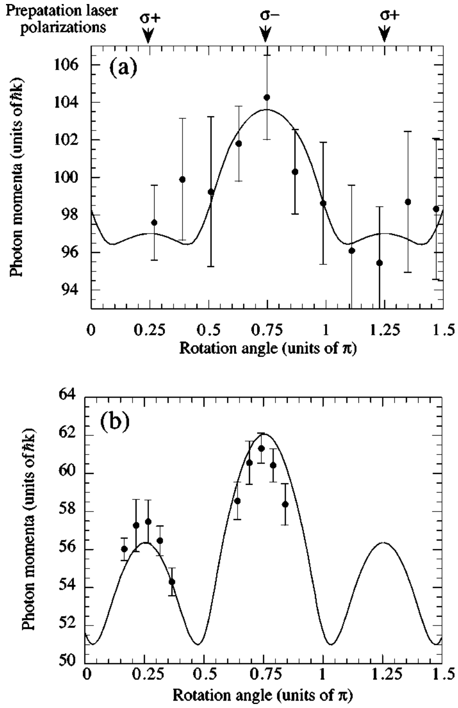

FIG. 3. Atomic deflections, in units of photon momenta, as a function of state preparation for two different tuning conditions of the preparation laser. The experimental measurements are represented by the dots and the lines are QED simulations using the conditions of the experiments. (a) Preparation laser detuned 9 MHz above the transition frequency. (b) Preparation laser detuned 3 MHz above the transition frequency.

measurement of $\rho_{22}-\rho_{-2-2}$, the deflection laser is circularly polarized. (The superscript L representing the laser frame of reference has been omitted for convenience). The atoms in the $3\ ^2S_{1/2}(F=2)$ state are deflected by both laser beams, while those in the $3\ ^2S_{1/2}(F=1)$ state are not. The deflection due to the preparation laser is about 25 photon momenta. The deflected distance is measured by fitting Gaussian curves to the detected peaks of the two states. The optical preparation is monitored by analyzing the atomic fluorescence with a polarizer and photomultiplier tube [15].

The chamber in which the preparation and deflection interactions take place is lined with μ-metal and surrounded by three pairs of mutually orthogonal Helmholtz coils. The residual magnetic field in the interaction regions is less than 10^{-8} T as measured by a Hall probe.

A simulation of the experiment is performed by dividing the flight path of the atoms into three regions. In the first, a QED calculation of the elliptically polarized state preparation is performed [15]. The second region allows for free travel of the atoms while in the third, a QED calculation of the deflection for a given polarization is carried out [11].

The results of deflection measurements in terms of transferred momenta are shown in Fig. 3. The data is taken as a function of the angle of rotation, β, of the quarter-wave plate, which determines the polarization of the preparation radiation. When the angle of the retarder is at $\pi/4$ and $5\pi/4$, the preparation radiation is left-hand circularly polarized. It is right-hand circularly polarized for an angle of $3\pi/4$. The deflection radiation is right-hand circularly polarized. In Fig. 3(a) the intensity of both the preparation and deflection laser beams was approximately 0.04 mW/mm^2. The preparation laser was detuned 9 MHz above the $3\ ^2S_{1/2}(F=2)-3\ ^2P_{3/2}(F=3)$ transition to reduce losses to the $3\ ^2S_{1/2}(F=1)$ ground state. The atoms had a mean velocity of 1000 m/s and a preparation time of 4 μs. The deflection laser was tuned to the frequency that produced the maximum deflection. This was about 3 MHz above the transition. The interaction time for the atoms in the deflection region was 8.5 μs. The solid curve is a calculation of the deflection for these experimental conditions using the simulation as described above. Note that the largest deflection is obtained for similar handedness of preparation and deflection radiation as previously observed [12].

Figure 3(b) shows deflection measurements for the same conditions as Fig. 3(a) except that the preparation laser is detuned only 3 MHz above the transition frequency. Under these tuning conditions, it is possible for the $3\ ^2P_{3/2}(F=2)$ state to be populated during the excitation process and so for atoms to relax to the $3\ ^2S_{1/2}(F=1)$ ground state. Once in this state, the atoms can no longer be excited or deflected. Hence the deflections at all rotation angles are reduced. The optical pumping loss is a minimum for circularly polarized radiation, as the atoms are rapidly pumped to the respective $3\ ^2S_{1/2}(F=2,m_F=\pm 2)-3\ ^2P_{3/2}(F=3,m_F=\pm 3)$ transitions in which they continue to cycle. The increase in the relative deflection for circularly polarized preparation is evident in Fig. 3(b). The calculation of the deflection for these is shown by the solid curve.

P_o can be constructed by repeating the deflection measurement with left-hand circularly polarized light and finding the difference at each angle. All measurements are normalized to the fraction of atoms that are deflected. The deflection parameter difference $D_{\sigma^+}^{-2-2}-D_{\sigma^+}^{22}$ does not depend on the state preparation. It can be determined experimentally from P_o when the atom is completely oriented, that is, when the atom has been completely prepared in either the $m_F=2$ or $m_F=-2$ substrates. Measurement of the line polarization of

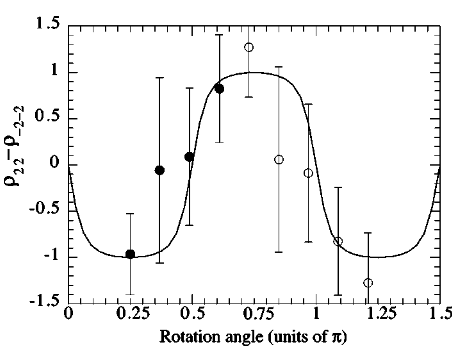

FIG. 4. Prepared population difference $3\ ^2S_{1/2}(F=2,m_F=2)-3\ ^2S_{1/2}(F=2,m_F=-2)$ as a function of the elliptical polarization of the preparation laser. The experimental data are determined from deflection data under the conditions of Fig. 3(a). The QED calculation is shown by the solid line. From the data, it can be seen that the atom is prepared in one substate only for preparation radiation that is circularly polarized. This is complete orientation of the atom.

the resonance fluorescence from the deflection region using a linear polarized and the photomultipier tube enables the settings for complete orientation to be made [15]. For the conditions of this experiment, the value of $D_{\sigma^+}^{-2-2} - D_{\sigma^+}^{22}$ was calculated to be 6.93 which was consistent with its measurement to within experimental error.

The experimental evaluation of the population difference $\rho_{22} - \rho_{-2-2}$ under the conditions of Fig. 3(a) is shown in Fig. 4. These data show that deflection measurements are sensitive to the polarization of the preparation laser and hence the atomic charge cloud shape. It can be seen from the figure that complete orientation of the atom is achieved for circularly polarized preparation.

Other density matrix elements can be determined by employing different deflection laser polarizations. For example, using the geometry of Fig. 2, but with linearly polarized radiation for deflecting the atoms, the $\rho_{2,0}$, $\rho_{0,-2}$, $\rho_{1,-1}$, and $\rho_{2,-2}$ elements can be obtained [16]. If more density matrix elements are necessary to reconstruct the quantum state of the atom, the deflection beam can be rotated out of the plane of the preparation laser beam and atomic beam. Transformation through the appropriate Euler angles to the relevant frame using rotation operators will enable a complete description of the density matrix to be obtained.

We have observed the sensitivity of photon deflection of a beam of atoms to their state preparation. We have discussed how this method can be employed to completely reconstruct the state of the atoms before deflection. This constitutes, among others, a method to determine atomic collision parameters for collisions between electrons and metastable atoms. Work is currently progressing to replace the sodium beam with a Zeeman cooled beam of metastable neon. This system will greatly increase the resolution of deflection measurements. The appropriate metastable transition in neon is closed, thus eliminating losses to nonparticipating states.

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