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Observation of Focusing of Neutral Atoms by the Dipole Forces of Resonance-Radiation Pressure

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For sodium atoms in an atomic beam, we demonstrate focusing, defocusing, and steering caused by the transverse dipole forces exerted by the radial intensity gradient of a superimposed and co-propagating resonant cw light beam. Dipole radiation-pressure forces differ from the forces due to spontaneous emission and are needed to achieve optical traps for neutral atoms.

We have observed that a cw laser beam superimposed upon and co-propagating with a beam of neutral atoms can cause substantial changes in the atomic trajectories when the light frequency is tuned near an atomic resonance. The atoms can be confined, ejected, or steered by the light beam. This new effect, the focusing of atoms by light, results from the same physical mechanism (momentum exchange) responsible for self-focusing of light in atomic vapors.[1] These deflections are caused by the transverse *dipole* resonance-radiation-pressure forces exerted on an induced dipole by an electric field gradient. Deflection of neutral atoms by dc field gradients is well known[2] and the deflection of neutral molecules by gradients of resonant microwave fields has been observed.[3] The analogous effects in atoms caused by resonant fields have not previously been observed, but they have been discussed lately in applications of light pressure.[4,5] Indeed, transverse dipole forces are important in proposed optical traps for neutral atoms.[5] Since the effects we observe are quite strong, other applications will also be apparent.

Dipole resonance-radiation pressure arises from stimulated light-scattering processes and exists only in optical field gradients; it thus differs fundamentally from spontaneous resonance-radiation pressure[6] which arises from spontaneous light scattering and which exists even in uniform resonant light fields. Spontaneous forces have been observed and discussed in many situations, for example, deflection of atoms,[6,7] cooling of atomic vapors,[8] induced density gradients in a vapor,[9] and isotope separation.[10] Recently, they have been used to cool ions contained in ion traps.[11] Both pressures, of course, derive from light momentum. However, the dipole force can be made the larger of the two forces.

A diagram of our experiment is shown in Fig. 1. Light from a continuously tunable, single-mode cw dye laser was superimposed upon an effusive atomic beam of neutral sodium using a 3-mm-thick dielectric-coated mirror with a 230-μm-diam hole in it. The light was focused by a 75-cm lens to a focal spot size $w_0 = 100\ \mu$m situated 25 cm from the mirror. The laser spot size on the mirror was 500 μm and the confocal parameter of the beam was 10 cm. Because the mirror was in the far field of the light, the dark spot in

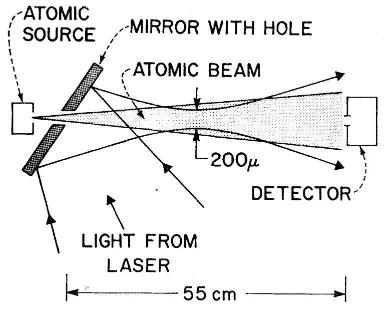

FIG. 1. Schematic diagram of experimental setup. Note the scale differences between the longitudinal and transverse directions.

the center of the reflected laser beam caused by the hole in the mirror was totally washed out in the near field of the light. Thus the laser intensity distribution was nearly Gaussian in the central 20-cm region where the interaction between the atoms and light predominantly took place. The laser was tuned near 5890 Å in order to excite the $3\,^2S_{1/2} \rightarrow 3\,^2P_{3/2}$ resonance transition. The atomic-beam profile was measured by a movable hot-wire detector. We found the detector to be insensitive to the incident light.

The time-averaged transverse dipole force exerted on a two-level atom can be obtained from the radial potential energy $U(r)$, given by[5]

$$U(r) = \tfrac{1}{2}h(\nu - \nu_0)\ln(1+p), \qquad (1)$$

where the atomic saturation parameter p is given by

$$p = \frac{\lambda^3}{\pi^3 hc\Delta\nu_N}\,\frac{\Delta\nu_N{}^2/4}{(\nu-\nu_0)^2 + \Delta\nu_N{}^2/4}\,\frac{P}{w^2}\exp(-2r^2/w^2).$$

Here ν and λ are the frequency and wavelength, P is the optical power, w is the Gaussian beam spot size, ν_0 is the atomic resonance frequency, and $\Delta\nu_N$ is the natural linewidth. For $\nu<\nu_0$, $U(r)$ is negative and atoms are pulled into regions of high light intensity; for $\nu>\nu_0$, atoms tend to be expelled from that region. The transverse forces can be appreciable; for $\nu<\nu_0$ and parameters typical of our experiment, $\lambda = 5890$ Å, $\Delta\nu_N = 10^7$ Hz, $w = 100$ μm, $P = 50$ mW, and $(\nu-\nu_0) = -2$ GHz, we find $p = 0.1$ and $U(0) = 6.9\times10^{-19}$ erg. This means that a sodium atom with a transverse velocity as great as 190 cm/sec can be confined transversely within the laser beam. While sodium is not a two-level atom, our experiment demonstrates that possible deleterious effects caused by optical pumping of the ground state are not important.

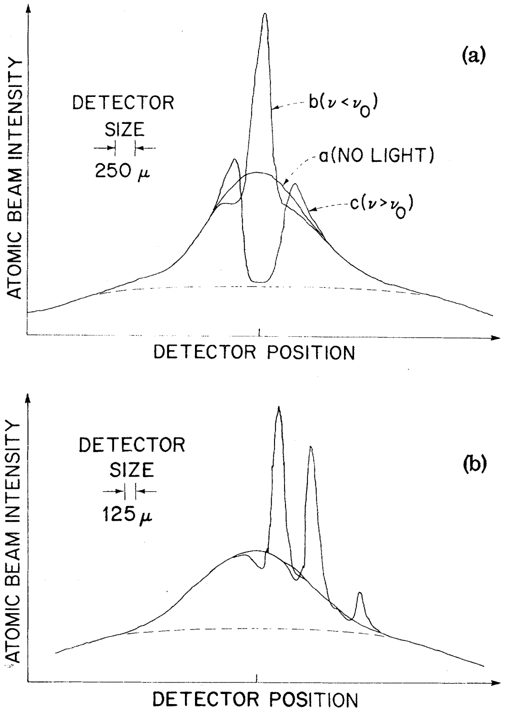

FIG. 2. (a) The atomic-beam current at the detector as a function of transverse detector position. The light dashed line shows the approximate background intensity. Peak beam current is approximately 2×10^8 atoms/sec. (b) The atomic-beam current as a function of transverse detector position for laser frequencies $\nu<\nu_0$, and various degrees of misalignment of the laser beam relative to the atomic beam.

The atomic-beam profile at the detector is shown in Fig. 2(a). The spatial resolution was set by a 250-μm-diam aperture on the detector; the narrow, intense peak in the atomic-beam intensity induced for $\nu<\nu_0$ and the dip induced for $\nu>\nu_0$ are almost fully resolved. As indicated by the above calculation and as demonstrated in Fig. 2(b), one can guide or steer the atoms by slightly changing the alignment of the laser beam relative to the atomic beam. Calculations show that for $\nu>\nu_0$ nearly all atoms should be expelled from the light beam. This is not observed in Fig. 2 because of background atoms superimposed upon the direct atomic beam; the approximate inferred background level is shown by the dashed lines. Atoms in the background apparently do not interact much, if at all, with the light. To remove the background and force any atom which reaches the detector to interact with the light we placed a 250-μm-diam aperture in the atomic beam, located at the focus of the laser beam. Results for these conditions, and with a 125-μm-diam aperture on the detector, are shown in Fig. 3. As expected, the atoms are almost totally expelled from the laser beam for $\nu > \nu_0$. (In a separate ion-counting experiment we have not been able to detect any photoionization of the atoms caused by the cw light.)

The on-axis atomic-beam intensity as a function of the laser tuning is shown in Fig. 4. The dispersionlike shape of this curve is in accord with Eq. (1). Within several GHz of resonance, the longitudinal force due to spontaneous light pressure is also important. This spontaneous force accelerates the atoms, which reduces the atomic-beam divergence and increases the on-axis atomic-beam intensity. Note the strong effects obtained for tunings more than 15 GHz away from resonance; only the transverse dipole forces are significant in these regions.

The height and width of the peak induced in the atomic-beam intensity distribution for $\nu < \nu_0$ have been roughly explained by approximating the potential of Eq. (1) to be harmonic. Ignoring the longitudinal acceleration due to spontaneous forces, the atomic trajectories in the interaction region are then sinusoidal with a typical oscillation frequency of 4 kHz. Thus, even atoms with a large longitudinal velocity execute more than a full oscillation cycle, and the interaction region can be considered as a distributed strong lens which guides and focuses the atoms by varying amounts depending on initial conditions. A simple calculation along these lines agrees qualitatively with our observations. This analysis predicts a strongly non-Maxwellian velocity distribution on axis. Spontaneous forces will also alter the velocity distribution. We have observed velocity-distribution changes in preliminary experiments using a slotted-disk velocity selector placed in front of the detector.

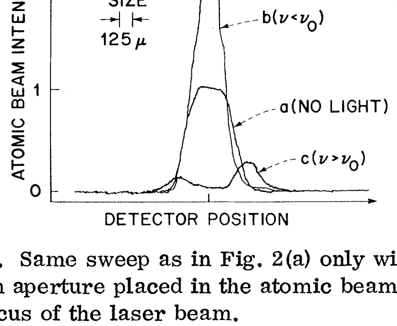

FIG. 3. Same sweep as in Fig. 2(a) only with a 250-μm-diam aperture placed in the atomic beam, located at the focus of the laser beam.

By observing changes of atomic trajectories in an atomic beam, we have directly observed the effects of transverse dipole resonance-radiation pressure. Dipole forces may cause important indirect effects in other types of experiments. For instance, the inclusion of transverse dipole forces seem to explain anomalies seen in experiments which observed pressure changes induced by radiation pressure in a long capillary filled with an atomic vapor.[9] It has also been suggested[12] that the density changes induced in a vapor by the dipole forces could cause distortions of line shapes observed in saturation spectroscopy. Whenever nonlinear optical effects are important, the effects of dipole forces may be observable.[13]

Finally, we discuss some possible applications of transverse dipole forces. First, applications to isotope separation are obvious; purification of materials by elimination of trace elements would also seem possible. Using the dipole forces, light beams can be used to confine and guide atoms; in conjunction with spontaneous forces, they can be used to construct optical traps and "bottles" for neutral atoms. An interesting situation would be the use of a TEM_{01} or "doughnut"-mode laser beam tuned to the high-frequency side of resonance. In this case, the atoms would be confined to the axis of the light beam where the intensity is a minimum. The use of a counterpropagating TEM_{00} laser beam would allow one to decelerate the atoms; this will increase the atomic beam divergence and will tend to destroy the beam. The use of transverse dipole forces for confinement (plus possible transverse cooling

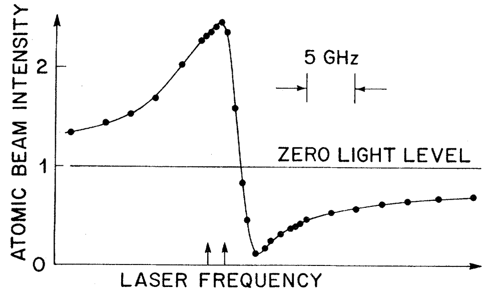

FIG. 4. The on-axis atomic-beam intensity as a function of laser frequency. The arrows mark the frequencies of the two resonance transitions $3^2S_{1/2}(F=2,1) \rightarrow 3^2P_{3/2}$ and are separated by approximately 1.77 GHz. The shift of the curve zero crossing relative to these frequencies is consistent with the longitudinal Doppler shifts of the atoms.

using additional light beams) might make it possible to create beams of ultraslow atoms. There may even by applications in molecular-beam epitaxy in which light beams are used to guide the atoms being deposited to desired locations. Of course, the discussion presented here is not restricted to neutral atoms; dipole forces are also exerted on neutral molecules and on ions.

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Extension of the Method of Complex Basis Functions to Molecular Resonances

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We consider the extension of the complex-coordinate technique to the problem of locating molecular resonances. We suggest a method which uses complex normalizable functions and which becomes equivalent to the usual dilatation transformation asymptotically, but is different for small values of the electronic coordinates. The technique is illustrated by application to the bound states of H_2^+ and to a model nonspherical resonance problem.

In a number of calculations the method of rotated coordinates has proved a useful and straightforward computational tool for the study of electronic resonance phenomena in atoms,[1] and it continues to attract considerable attention in the literature. But in spite of the simplicity of the method, we know of no extension which permits its application to molecular autoionizing states. This assertion requires some clarification, particularly since the current literature is so circumspect on the subject that one can find almost no discussion of the difficulties involved.

The now familiar theorems of Balslev and Combes[2] and Simon,[3] which form the mathematical basis of the rotated-coordinate approach, apply to the Hamiltonian of any system of particles interacting via Coulomb potentials with the center-of-mass motion removed. The replacement of every coordinate $\vec{r}_j$ by $e^{i\theta}\vec{r}_j$ leads to an N-particle Hamiltonian whose discrete spectrum consists of real bound-state eigenvalues and isolated resonance eigenvalues, and whose continuous spectrum is a series of rays in the complex energy plane beginning at the bound-state energies of the $(N-1)$-particle system [and $(N-2)$ particle system, etc.] and making an angle of 2θ with the