Momentum transfer to atoms by a standing light wave: Transition from diffraction to diffusion

Phillip L. Gould,* Peter J. Martin,† George A. Ruff,‡ Richard E. Stoner, Jean-Louis Picqué,§ and David E. Pritchard
Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 20 August 1990)

Momentum transfer to atoms by a standing light wave is measured in the presence of spontaneous decay. As the number of spontaneous decays is increased, the well-known Kapitza-Dirac diffractive structure observed in the absence of spontaneous decay evolves into a smooth diffusive pattern. Theoretical treatments based on a diffusive model adequately describe the rms momentum transfers and the envelopes of the momentum distributions. However, we observe significant persistence of diffractive structure at our long interaction times and find that details of the deflection profiles are accurately predicted only when several spontaneous decays occur during the interaction.

The forces on atoms by light have recently received much theoretical and experimental attention,[1,2] not only because of interest in the basic atom-light interaction, but also because these forces offer ways to slow, cool, and trap neutral atoms. We present here high-resolution measurements of the deflection of an atomic beam by a plane standing light wave that show how the momentum transfer to the atom changes from diffractive to diffusive as the number of spontaneous decays during the interaction is increased. These measurements represent a quantitative test of diffusion-based light force theories that must be applied when spontaneous emission plays an important role. Such diffusive theories do not predict the considerable persistence of diffractive structure that we observe at our long interaction times. On the other hand, these theories predict the rms momentum transfer within the 15% experimental uncertainties and agree qualitatively with diffractive-averaged envelopes of the observed deflection profiles. Quantitative agreement between measured and predicted momentum distributions is obtained under conditions where many spontaneous decays occur.

Forces on atoms due to light are generally separated into two types, the spontaneous force (radiation pressure) and the dipole force. The dipole force is due to the interaction of the atom's induced dipole moment with (the gradient of) the light amplitude and is by far the more significant force in a standing light wave, the configuration used in our experiment. (In fact, the average spontaneous force vanishes everywhere in a standing wave—only its fluctuations remain.) Recent experiments involving the dipole force in a standing wave have focused on the velocity dependence of the force[3] and the ability of the standing wave to redistribute[4] and channel[5] atoms. In the present work, we probe the effects of spontaneous decay on the spatially dependent dipole force, thereby extending our previous measurements of diffraction[6,7] into the diffusive regime.

The dressed-atom approach provides the most physical description of dipole light forces.[8] The two "dressed" states have an induced dipole moment aligned parallel and antiparallel to the oscillating light field, resulting in an attraction towards higher and lower light intensities, respectively. In the absence of spontaneous emission the atoms remain in one dressed state, experiencing a unidirectional force which varies with the local intensity gradient. Spontaneous emission can cause transitions between the dressed states resulting in random changes in the sign of the dipole force. The time-averaged dipole force is proportional to the population difference of the dressed states and goes to zero at zero detuning. Spontaneous transitions between these states result in force fluctuations, leading to "induced" diffusion in the momentum distribution. In addition to the fluctuations in the dipole force, there are fluctuations due to the random recoil from spontaneously emitted photons.[9] These fluctuations are the only manifestation of the spontaneous force in our experiment; they give rise to "spontaneous" diffusion in the momentum distribution.

Although the spontaneous fluctuations are always more than an order of magnitude smaller than the induced fluctuations in our experiment, their effect is very noticeable in our data because they are solely responsible for the transition from a multipeaked diffractive momentum distribution to a smooth diffusive distribution. This observation, apparently not mentioned in previous theoretical treatments, may be understood by using a quantum view of the light, in which momentum is transferred to the atom by photons, each with momentum $\hbar k$. Since the dipole force and its fluctuations (induced diffusion) result from momentum exchanged by absorption and stimulated emission of photon *pairs*, the projection of this momentum along the laser axis (for our plane standing wave) is quantized in integral multiples of $2\hbar k$. Hence induced diffusion does not contribute to the blurring of the multipeaked diffractive structure. On the other hand, spontaneous recoil occurs in a random direction so that its momentum component along the direction of the standing wave[9] can range from $-\hbar k$ to $+\hbar k$. Thus spontaneous diffusion imparts momentum with a continuous distribution which fills in the minima between the peaks at $2n\hbar k$, smoothing the final momentum distribution and completing the transition to the diffusive regime.

A complementary view of the quantized momentum

distribution described above arises when both light and atoms are viewed as waves. The periodic light intensity now acts as a phase grating with spatial period $\lambda/2$, leading to atomic diffraction[6,7] with period $2\hbar k$. In this view the diffraction may be said to arise from the interference of waves which scatter from similar parts of the grating spaced apart by $\lambda/2$. The loss of the diffractive structure then results from the loss of coherence between portions of the atom wave which scatter from different parts of the potential, a loss which originates solely from the spontaneous decay.

The experiments are performed on the apparatus previously described.[6,7,10] A monoenergetic [$\Delta v/v = 11\%$ full width at half maximum (FWHM)], highly collimated ($1.0\hbar k$ FWHM), optically pumped[10] atomic sodium beam is deflected by a well-characterized, circularly polarized standing light wave. Experimental results are shown in Fig. 1. The transition from diffraction [Fig. 1(c)] to diffusion [Fig. 1(a)] is made by tuning closer to resonance, thereby increasing $\bar{N}$, the average number of spontaneous

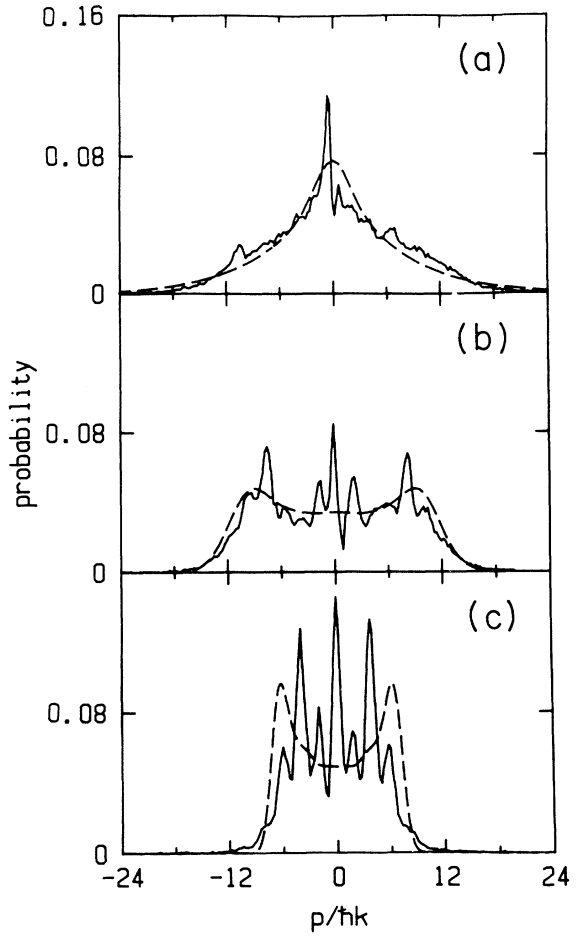

FIG. 1. Experimental data (solid lines) of transverse momentum transfer to an atomic beam by a standing light wave for different values of $\bar{N}$, the average number of spontaneous decays during the interaction. (a) $\Delta=0$, $\Omega_0=2.36\Gamma$, $\bar{N}=4.48$; (b) $\Delta=4.0\Gamma$, $\Omega_0=3.34\Gamma$, $\bar{N}=1.15$; (c) $\Delta=8.0\Gamma$, $\Omega_0=3.34\Gamma$, $\bar{N}=0.40$. The interaction time is $\Gamma\tau=4.71$ for all scans. Dashed lines are theoretical predictions [Eq. (5)].

decays in the interaction region. All three curves have the same interaction line.

There are two key elements to be considered when the transition is made by changing the detuning at a fixed interaction time. First, as we tune closer to resonance, the time-averaged dipole force weakens while its fluctuations grow. This causes a qualitative change in the envelope of the deflection profile as two symmetric peaks [Fig. 1(c)] coalesce into one [Fig. 1(a)]. The second consideration involves the manner in which the increasing [from Fig. 1(c) to 1(a)] value of $\bar{N}$ fills in the momentum distribution between the δ functions located at $2\hbar k$ intervals. Both considerations indicate that it is the number of spontaneous decays and not simply the length of interaction time that is the important factor in making the transition.

The theoretical description of momentum transfer in a standing wave is complicated by the stochastic nature of spontaneous emission. Therefore, fully quantum-mechanical descriptions of the momentum-transfer process[6,7,11] (which yield quantized momentum distributions) are replaced by a Fokker-Planck approach[12–14] in which the momentum is treated classically, i.e., as a continuous variable. This diffusive theory has been applied to the standing-wave problem by several authors.[15–18] A brief synopsis of this "standard" theory, generalized for arbitrary laser profile, is given here. We note that Ref. 16 has specifically addressed the transition regime and solved the problem in principle, but computational complexities have prevented direct comparisons with experiment.

The electric field that an atom is subjected to as it moves through the standing light wave is given by

$$E(x,t)=2E_0 f(t)\cos(kx)\cos(\omega t)\ . \tag{1}$$

In this expression $f(t)$ describes the time dependence of the field amplitude due to the atom's passage (along $\hat{\mathbf{y}}$) through the laser beam with velocity v. The laser profile is Gaussian: $f(t)=e^{-(t/\tau)^2}$, where τ is the transit time for the $1/e^2$ radius of intensity.

For a two-state atom (energy difference $\hbar\omega_0$) interacting (via dipole moment μ) with the electric field of Eq. (1), there are three relevant frequencies: the spontaneous decay rate Γ ($\Gamma/2\pi=10$ MHz), the laser detuning $\Delta=\omega-\omega_0$, and the Rabi rate $\Omega_0=\mu E_0/\hbar$, due to one of the two counterpropagating traveling waves which combine to form the standing wave. Defining $r=\Gamma^2/(\Gamma^2+4\Delta^2)$ and $s(x,t)=s_0 f^2(t)\cos^2(kx)$, with $s_0=8\Omega_0^2/(\Gamma^2+4\Delta^2)$, the dipole force is[15,16]

$$F(x,t)=-\frac{\hbar\Delta}{2(1+s)}\frac{ds}{dx} \tag{2}$$

and the contributions to the momentum diffusion coefficient, $D=D_I+D_S$, from induced processes (D_I) and spontaneous recoil (D_S) can be written[12,15]

$$D_I(x,t)=\frac{\hbar^2\Gamma}{16s(1+s)^3}\left[\frac{ds}{dx}\right]^2\left[1+(4r-1)s+3s^2+\frac{s^3}{r}\right], \tag{3a}$$

$$D_S(x,t)=\frac{\hbar^2k^2}{10}\Gamma\frac{s}{1+s}\ . \tag{3b}$$

Considering an atom crossing the standing wave at a point x, the dipole force [Eq. (2)] will impart an average transverse momentum $p_F(x)$ to the atom over the course of the interaction. In addition, the dispersion of the atomic momentum $p_D^2(x)$ will increase as a result of momentum diffusion [Eq. (3)]. Solution of the Fokker-Planck equation[15] yields a Gaussian momentum-transfer distribution centered at $p_F(x)$ with rms width $p_D(x)$. In our experiment the change of x during the interaction is much less than λ hence the average value and dispersion of the atomic momentum are given by

$$p_F(x)=\int_{-\infty}^{\infty} F(x,t)dt \ , \tag{4a}$$

$$p_D^2(x)=p_I^2(x)+p_S^2(t)=2\int_{-\infty}^{\infty}[D_I(x,t)+D_S(x,t)]dt \ , \tag{4b}$$

where we have separated the contributions to the dispersion from induced diffusion and spontaneous recoil. Since the extent (along x) of the atomic beam is much greater than λ and the initial momentum distribution is much narrower than the distribution of momentum transfers [determined by Eq. (4)], the final momentum distribution $P(p)$ is just the average of Gaussians centered at $p_F(x)$ and having dispersion $p_D^2(x)$:[15]

$$P(p)=\frac{2}{\lambda}\int_{-\lambda/4}^{+\lambda/4}dx\left[\frac{1}{2\pi p_D^2(x)}\right]^{1/2} \times\exp\left[\frac{-[p-p_F(x)]^2}{2p_D^2(x)}\right] . \tag{5}$$

The rms momentum transfer $p_{\rm rms}$ is easily calculated from this momentum distribution:

$$p_{\rm rms}^2=\int_{-\infty}^{\infty}dp\,p^2P(p)=\frac{2}{\lambda}\int_{-\lambda/4}^{\lambda/4}dx[p_F^2(x)+p_D^2(x)] =\overline{p_F^2}+\overline{p_I^2}+\overline{p_S^2} , \tag{6}$$

where the contributions from the dipole force, induced diffusion, and spontaneous recoil have been separated. The relative contributions of the three terms are plotted as functions of detuning in Fig. 2.

The various contributions to $p_{\rm rms}^2$ may be isolated as follows: on resonance, the force term vanishes while the diffusive terms are maximized; whereas for $\Delta>\Omega_0$, the diffusive terms vanish more rapidly than the force term. Therefore momentum-transfer measurements at small and large values of Δ are primarily observations of the diffusive and force terms, respectively. We note that spontaneous recoil contributes negligibly to $p_{\rm rms}$; its only observable effect is to smooth the diffraction peaks.

The theoretical predictions given by Eq. (5) (with no free parameters) are shown as the dashed curves in Fig. 1. Since the momentum is treated classically, diffraction is not included—probabilities instead of probability amplitudes are summed in Eq. (5). This theory yields a smooth prediction for momentum transfer with the double-peaked structure[19] in Fig. 1(c) changing to a diffusive single-peaked distribution in Fig. 1(a).

The rms momentum transfer for two values of laser power are plotted as a function of Δ in Fig. 3. The theoretical fits in Fig. 3 are derived from Eq. (6), again with no free parameters. The error bars on the data reflect only the uncertainties in the measurement of $p_{\rm rms}$.

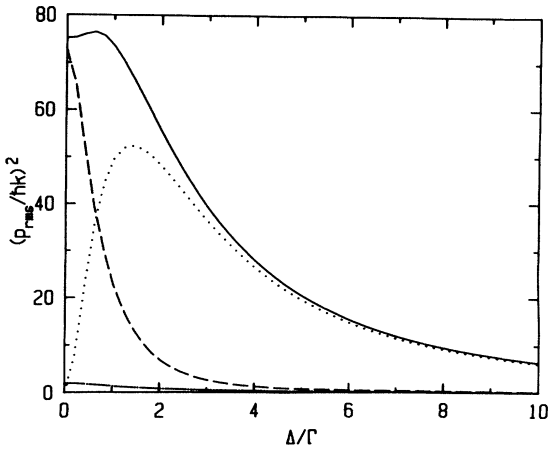

FIG. 2. Contributions to the total mean-squared momentum (solid line) from the dipole force (dotted line), induced diffusion (dashed line), and spontaneous recoil (dash-dotted line). For these plots $\Omega_0=2.49\Gamma$ and $\Gamma\tau=4.71$, implying that $\bar{N}=1$ for a detuning of $\Delta=3.5\Gamma$.

Uncertainties in parameters of the interaction cause about a 7% uncertainty in the theoretical curves (not shown). The largest contribution to this is a 5% error in measuring the absolute laser power. Considering the experimental and theoretical errors, we do not view the slight systematic deviation of the data from the theoretical curves as significant.

In conclusion, we have observed the transition from diffractive to diffusive behavior in the momentum transfer to an atomic beam by a standing light wave. In the absence of spontaneous decays, the dipole force dominates and diffraction with a two-peaked envelope results. With increasing spontaneous decays, fluctuations of the dipole force (with momentum still imparted in units of $2\hbar k$) assume the dominant role and lead to a single-peaked distribution. Diffractive structure is washed out

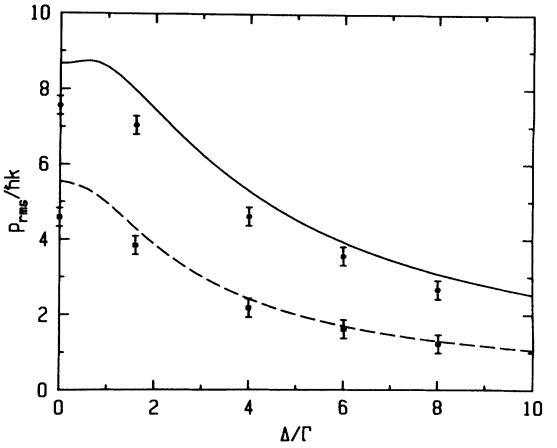

FIG. 3. rms momentum vs Δ for two values of laser power. The solid line is the theoretical prediction for $P=475$ μW ($\Omega_0=2.49\Gamma$) and the dashed line is the prediction for $P=190$ μW ($\Omega_0=1.57\Gamma$). Experimental data points taken at $P=475$ μW (circles) and $P=190$ μW (squares) are also shown. $\Gamma\tau=4.71$ for both data and predictions. For the high and low powers, $\bar{N}=1$ for detunings of $\Delta=3.5\Gamma$ and 2.2Γ, respectively.

solely by spontaneous recoil, but only after several spontaneous decays. Deflection profile envelopes and rms momentum transfers are in general agreement with theoretical predictions based on the Fokker-Planck diffusion equation, but details of deflection profiles are accurately predicted only in the diffusive limit. The persistence of diffractive structure is not accounted for in this type of theory, and remains a challenge to theory. Our results point out that the transition from diffraction to diffusion involves the number of spontaneous decays and not simply the length of interaction.

We gratefully acknowledge the support of the National Science Foundation through Grants No. PHY83-07172-A01 and No. PHY-8514748 (Research Opportunity Award Program).

---

*Present address: Department of Physics, University of Connecticut, Storrs, CT 06269.

†Present address: Joint Institute for Laboratory Astrophysics, University of Colorado, Boulder, CO 80309-0440.

‡Permanent address: Department of Physics, Bates College, Lewiston, ME 04240.

§Permanent address: Laboratoire Aimé Cotton, Centre National de la Recherche Scientifique, F-91405 Orsay, France.

[1]J. Opt. Soc. Am. B **2** (Feature Issue: The Mechanical Effects of Light), Nov. 1985; J. Opt. Soc. Am. B **6** (Feature Issue: Laser Cooling and Trapping of Atoms), Nov. 1989.

[2]S. Stenholm, Rev. Mod. Phys. **58**, 699 (1986).

[3]A. Aspect, J. Dalibard, A. Heidmann, C. Salomon, and C. Cohen-Tannoudji, Phys. Rev. Lett. **57**, 1688 (1986); J. W. Early, Opt. Commun. **65**, 250 (1987); M. Prentiss and A. Cable, Phys. Rev. Lett. **62**, 1354 (1988).

[4]M. G. Prentiss and S. Ezekiel, Phys. Rev. Lett. **56**, 46 (1986).

[5]C. Salomon, J. Dalibard, A. Aspect, H. Metcalf, and C. Cohen-Tannoudji, Phys. Rev. Lett. **59**, 1659 (1987); V. I. Balykin, V. S. Letokhov, Yu.B. Ovchinnikov, A. I. Sidorov, and S. V. Shul'ga, Opt. Lett. **13**, 958 (1988).

[6]P. L. Gould, G. A. Ruff, and D. E. Pritchard, Phys. Rev. Lett. **56**, 827 (1986).

[7]P. J. Martin, P. L. Gould, B. G. Oldaker, A. H. Miklich, and D. E. Pritchard, Phys. Rev. A **36**, 2495 (1987).

[8]J. Dalibard and C. Cohen-Tannoudji, J. Opt. Soc. Am. B **2**, 1707 (1985).

[9]L. Mandel, J. Opt. (Paris) **10**, 51 (1979).

[10]P. L. Gould, G. A. Ruff, P. J. Martin, and D. E. Pritchard, Phys. Rev. A **36**, 1478 (1987).

[11]A. Dulcie, J. Eberly, H. Huang, J. Javanainen, and L. Roso-Franco, Phys. Rev. Lett. **56**, 2109 (1986).

[12]R. J. Cook, Phys. Rev. A **22**, 1078 (1980).

[13]J. Javanainen and S. Stenholm, Appl. Phys. **21**, 35 (1980).

[14]V. S. Letokhov and V. G. Minogin, Phys. Rep. **73**, 1 (1981).

[15]C. Tanguy, S. Reynaud, M. Matsuoka, and C. Cohen-Tannoudji, Opt. Commun. **44**, 249 (1983).

[16]C. Tanguy, S. Reynaud, and C. Cohen-Tannoudji, J. Phys. B **17**, 4623 (1984).

[17]V. G. Minogin, Opt. Commun. **37**, 442 (1981).

[18]A. P. Kazantsev, G. I. Surdutovich, and V. P. Yakovlev, J. Phys. (Paris) **42**, 1231 (1981).

[19]The overall bifurcation of the beam may be viewed as a "rainbow" effect caused by a stationary point (as a function of x) in the dipole force [Eq. (2)] at its maximum value. This is discussed in P. E. Moskowitz, P. L. Gould, and D. E. Pritchard, J. Opt. Soc. Am. B **2**, 1784 (1985).