Diffraction of Atoms by Light: The Near-Resonant Kapitza-Dirac Effect

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We have observed the Kapitza-Dirac effect in the scattering of sodium atoms by a near-resonant standing-wave laser field. The data clearly show diffraction peaks of the atomic momentum transfer at even multiples of the photon momentum. Theoretical predictions for an off-resonant, adiabatic interaction with a two-state system are in reasonable agreement with the data.

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Kaptiza and Dirac[1] predicted in 1933 that an electron beam would reflect from a standing light wave as a result of stimulated Compton scattering. Widespread interest in this prediction arose because the phenomenon is the quantum mechanical dual of diffraction of light waves by a matter grating—i.e., it is the diffraction of matter waves from a light grating—and also because it involves a stimulated radiative process. There have been several inconclusive attempts to observe this effect with use of electrons,[2] but classical[3] and quantum mechanical[4] theories have remained largely unverified.

Following a suggestion[5] that similar diffraction should occur for neutral atoms, we have chosen to investigate this process with an atomic sodium beam and near-resonant laser radiation. Our motivations for performing this experiment include the original interests of Kapitza and Dirac as well as a desire to provide definitive experimental tests to complement the contemporary proliferation of theoretical work on momentum transfer to atoms from radiation.[6]

Our experiment, although not the first deflection study with standing waves,[7–11] is the first in which the experimental conditions are sufficiently well defined to permit a clear-cut comparison with theory: A velocity-selected beam of two-state atoms interacts with a well-characterized standing wave, and the momentum transfer is measured with high resolution. Our results clearly demonstrate the quantization of the momentum transfer in even multiples of the photon's momentum; moreover, the amplitudes of the peaks are in good agreement with the predictions for our off-resonant, adiabatic interaction.

Although momentum transfer between an atomic beam and a standing-wave radiation field has received a great deal of theoretical attention,[12–19] only Refs. 13 and 18 have considered the combined circumstances of off-resonant excitation and adiabatic travel through the field, and neither has given an expression for amplitudes of even peaks for a smooth field profile.

We now outline a calculation[20] of the momentum transferred to a two-state atom (energy difference $\hbar\omega_0$, dipole moment μ) by a standing-wave electric field with temporal envelope $f(t)$:

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

The atoms move in the y direction. If their net displacement along x as they traverse the light beam is much smaller than a wavelength, then x becomes a parameter in the time-dependent Schrödinger equation for the ground- and excited-state amplitudes, $a_g(x,t)$ and $a_e(x,t)$. For $f(t)=\operatorname{sech}(t/\tau)$, the final ($t=+\infty$) amplitudes for an atom initially ($t=-\infty$) in the ground state can be expressed in terms of hypergeometric functions[21,22] involving the detuning, $\Delta=\omega-\omega_0$, and the peak traveling-wave Rabi rate, $\Omega_0=\mu E_0/\hbar$.

The probability, P_n, that the atom gains transverse momentum $n\hbar k$ from the interaction is obtained by expansion of this wave function in a Fourier series in x. For n odd (i.e., the atom emerges in an excited state), we find[13] that

$$P_n=\operatorname{sech}^2(\pi\Delta\tau/2)J_n^2(\pi\Omega_0\tau), \quad n \text{ odd}, \tag{2}$$

which is $<10^{-20}$ in our experiment. For n even (i.e., the atom emerges in the ground state), and for large detuning, we obtain

$$P_n=J_{n/2}^2(z)=J_{n/2}^2(\Omega_0^2\tau/\Delta), \quad n \text{ even}. \tag{3}$$

For generalization of Eq. (3) to an arbitrary $f(t)$, the argument of the Bessel function becomes

$$z=(1/2\Delta)\int_{-\infty}^{\infty}[\Omega_0 f(t)]^2dt, \tag{4}$$

which gives the correct result for a square field profile [$f(t)=1$ for a time τ] with adiabatic entry and exit and large detuning.[11,18] Thus, for our Gaussian profile, $f(t)=e^{-(t/\tau)^2}$, we find that

$$z=(\pi/8)^{1/2}\Omega_0^2\tau/\Delta. \tag{5}$$

Using a summation property for Bessel functions,[12] we can calculate the rms momentum from Eq. (3):

$$p_{\rm rms}=\left(\sum_{n=-\infty}^{\infty}(n\hbar k)^2P_n\right)^{1/2}=2^{1/2}z\hbar k. \tag{6}$$

The effects of spontaneous decay[19] are avoided by our operating sufficiently far from resonance to keep $\bar{N}$, the average (over x) number of decays during the interaction, less than 0.25.

In our experiment a collimated beam of sodium atoms is deflected by a plane standing-wave laser field. The transverse momentum distribution is determined by the scanning of a hot-wire detector downstream from this interaction. The apparatus[9,11] has been improved as follows: (1) momentum resolution (FWHM) of $0.71\hbar k$ by use of two 10-μm slits and a 25-μm detector spaced by ~ 0.9 and ~ 1.4 m, respectively; (2) velocity spread of the Na beam reduced to 11% FWHM by seeding in an Ar supersonic jet[11]; (3) experimental realization of the two-state system, $3\,^2S_{1/2}, F=2, m_F=2 \leftrightarrow 3\,^2P_{3/2}, F'=3, m_F'=3$, by use of optical pumping to transfer $\sim 90\%$ of the $F=2$ atoms into the $m_F=2$ state and state-selective radiative deflection to reduce the fraction of atoms in $F=1$ (or in dimers) to $\sim 6\%$[23]; (4) well-characterized Gaussian laser profile with fine adjustment of the parallelism of field nodes and atomic beam; (5) computer control of the detector scan—all data reported here were taken with a 1-sec dwell time and 10-μm steps of the detector, corresponding to $0.24\hbar k$ of deflection.

The deflecting radiation field was produced by focusing (with a cylindrical lens) of the elliptically expanded and circularly polarized Gaussian beam from a single-mode dye laser (Coherent 599-21) onto a flat mirror. Focused waists of 70 and 44 μm (e^{-2} radii of intensity) were used, resulting in τ's of ~ 70 and ~ 45 ns. The collimated vertical waist was 3.6 mm for both cases. The close proximity (~ 5 mm) of the atomic beam to the flat mirror (relative to the confocal parameter of the focused waist) and precise control of the angle of the mirror ($\sim 10^{-5}$ rad using a PZT drive) allowed realization of a plane standing wave with wave fronts parallel to the atomic beam. The detuning of the deflecting laser was always *below* the $F=2 \rightarrow F'=3$ resonance to ensure that $F=1$ atoms did not contribute to the deflection signal.

The experimental results are presented in Figs. 1–3 and in Table I. Diffraction patterns for three different values of the parameter z are shown in Fig. 1. The data are corrected for background and undeflected $F=1$ atoms. The details of these subtractions are derived from a close examination of the raw undeflected beam profile and their effect can be seen in Fig. 1(a). All of these scans exhibit a slight displacement of the diffraction peak at $+2\hbar k$, an isolated artifact due to a reproducible nonlinearity in the detector drive. The theoretical curves in Figs. 1(b) and 1(c) are obtained by convolution of the result of Eq. (3) with the measured atomic beam profile (FWHM of $0.71\hbar k$) and velocity distribution ($\Delta v/v$ FWHM of 11%).

Table I displays parameters for scans taken over a wide range of laser powers and detunings and at two different interaction times. The conversion from laser intensity, I, to Ω_0 is[24]

$$\Omega_0/2\pi = (10\ \mathrm{MHz})[I/(12.7\ \mathrm{mW/cm^2})]^{1/2}.$$

For all data we have had to divide the value of z calculated with Eq. (5) by a factor of 2 to obtain theoretical predictions in good agreement with the experiment. We are confident that the calculated values of z are correct to within 20%, where the principal error arises from uncertainties in the absolute laser intensity. At this time, we have no explanation for this discrepancy,

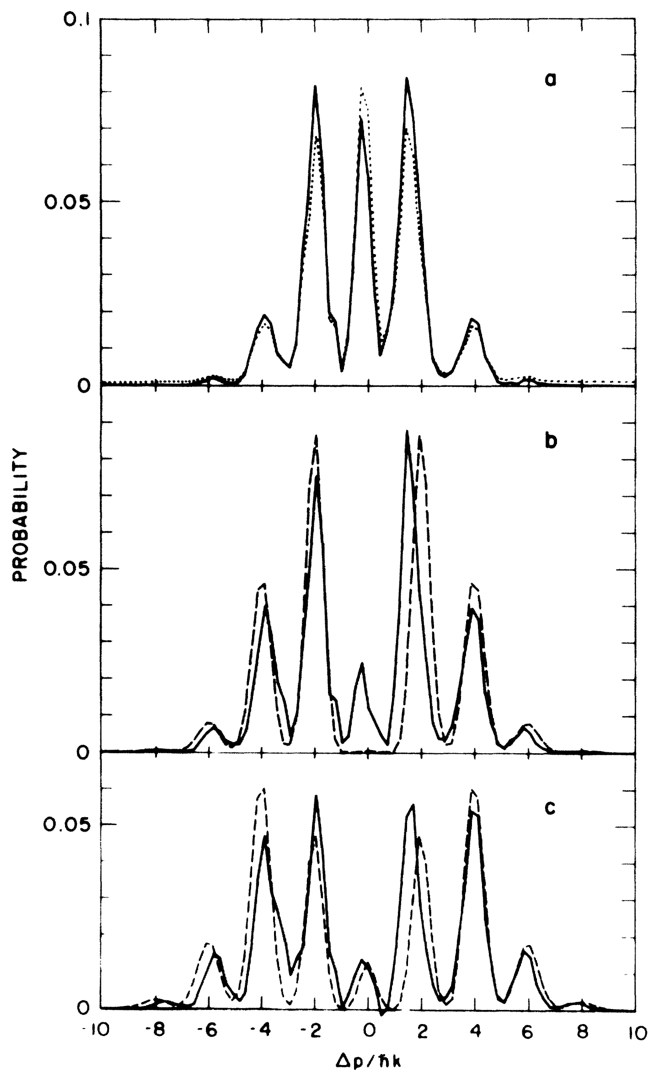

FIG. 1. Atomic diffraction patterns corresponding to the following scans (listed in Table I): (a) scan A4, (b) scan A5, (c) scan A3. In (a) the raw (dotted line) and corrected data (solid line) are compared. In (b) and (c) we display the theoretical fits (dashed line), described in the text, and the corrected data (solid line). All curves are normalized. A typical count rate is $\sim 10^6$ atoms/sec per scan.

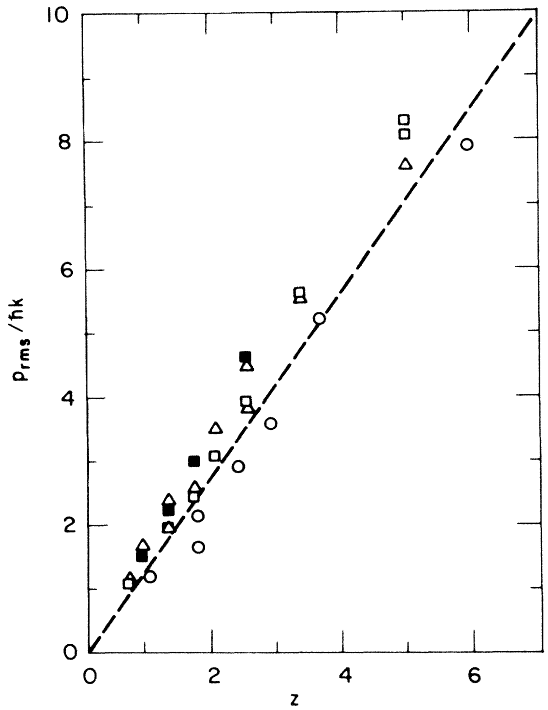

FIG. 2. rms momentum vs z. Data points from Table I are depicted by circles, run A; squares, run B; and triangles, run C. The filled squares represent scans B1, B2, B3, and B4, and their significance is discussed in the text. The dashed line is Eq. (6).

which is quite constant in different runs and at the two interaction times studied. Studies of traveling-wave deflection and the effects of optical misalignment are under way in an attempt to determine its origin. The values of z in Table I and Figs. 1 and 2 have been divided by this factor of 2.

The rms momentum for each scan is plotted as a function of z, along with Eq. (6), in Fig. 2. The agreement between theory and our experimental results is reasonable except for the factor of 2.

In our theory the deflection pattern and p_{rms} are determined solely through the parameter z [Eq. (5)]. We have been able to verify the predicted Δ^{-1} dependence of p_{rms} to within 5% (standard deviation) by restricting attention to data taken within one run (e.g., the filled squares in Fig. 2) whose other parameters are held constant. Since Ω_0^2 is proportional to laser intensity, our use of cylindrical optics results in $\Omega_0^2\tau$ being independent of τ at a fixed laser power. Comparing scans from runs B and C (Table I) with identical values of $\Omega_0^2\tau$ (i.e., laser power) and Δ, we find values of p_{rms} which agree to within 4% (standard deviation). In addition, this comparison reveals nearly identical diffraction patterns, an example of which is shown in Fig. 3. In general, the agreement between measured and predicted diffraction patterns is improved by our

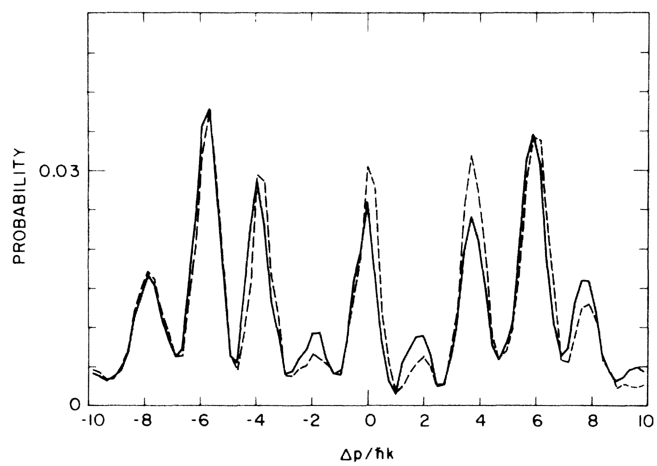

FIG. 3. Diffraction patterns for scans B8 (solid line) and C2 (dashed line) from Table I. The curves correspond to identical laser powers and detunings but different values of τ.

TABLE I. Parameters for individual diffraction patterns. Data were taken in three runs. For run A, $\tau = 4.5\Gamma^{-1} = 72$ ns; run B, $\tau = 4.4\Gamma^{-1} = 71$ ns; run C, $\tau = 2.8\Gamma^{-1} = 45$ ns. The scans are listed in the order recorded.

Scan	Power (mW)	$\Omega_0/2\pi$ (MHz)	$\Delta/2\pi$ (MHz)	$\bar{N}$	z	$p_{rms}/\hbar k$
A1	9.0	135	−444	0.24	5.91	7.92
A2	9.0	135	−731	0.09	3.59	5.23
A3	9.0	135	−922	0.06	2.84	3.59
A4	2.0	64	−349	0.09	1.69	2.16
A5	2.0	64	−253	0.17	2.33	2.92
A6	0.5	32	−157	0.11	0.94	1.21
A7	2.0	64	−349	0.09	1.69	1.66
B1	1.6	57	−186	0.24	2.48	4.64
B2	1.6	57	−279	0.11	1.65	3.01
B3	1.6	57	−372	0.06	1.24	2.24
B4	1.6	57	−558	0.03	0.83	1.52
B5	0.4	28	−93	0.24	1.24	1.97
B6	0.4	28	−186	0.06	0.62	1.10
B7	6.4	114	−372	0.24	4.96	8.30
B8	6.4	114	−558	0.11	3.31	5.64
B9	6.4	114	−744	0.06	2.48	3.94
B10	6.4	114	−930	0.04	1.98	3.08
B11	6.4	114	−1116	0.03	1.65	2.45
B12	6.4	114	−372	0.24	4.96	8.08
C1	6.4	144	−372	0.23	4.96	7.61
C2	6.4	144	−558	0.11	3.31	5.55
C3	6.4	144	−744	0.06	2.48	3.87
C4	6.4	144	−930	0.04	1.98	3.52
C5	6.4	144	−1116	0.03	1.65	2.58
C6	1.6	72	−186	0.23	2.48	4.49
C7	1.6	72	−279	0.11	1.65	3.02
C8	1.6	72	−372	0.06	1.24	2.39
C9	1.6	72	−558	0.03	0.83	1.67
C10	0.4	36	−93	0.23	1.24	1.96
C11	0.4	36	−186	0.06	0.62	1.17

choosing the value of z which corresponds [according to Eq. (6)] to the measured value of $p_{\rm rms}$, which confirms the predicted Bessel function pattern [Eq. (3)].

The sharp quantization of the transferred momentum can be interpreted as the diffraction of the atomic de Broglie waves by the intensity grating of the standing wave, which diffracts at $2\hbar k$ intervals as a result of its periodicity of $\lambda/2$. In a complementary view, the $2\hbar k$ quantization arises from absorption and stimulated emission of photon pairs from the counterpropagating traveling waves. Ironically these complementary explanations would have been equally unpalatable to a nineteenth century physicist: Either the atoms must be regarded as waves or the light as particles.

In conclusion, we have observed the near-resonant Kaptiza-Dirac effect using a beam of sodium atoms and a standing-wave laser field, under conditions where spontaneous emission can be ignored. Individual diffraction patterns are in good agreement with our theoretical predictions and the dependence of the rms deflection on laser power and frequency is consistent with the theory except for the factor of 2.

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