Observation of the Kapitza–Dirac effect

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In their famous 1927 experiment, Davisson and Germer observed[1] the diffraction of electrons by a periodic material structure, so showing that electrons can behave like waves. Shortly afterwards, Kapitza[2] and Dirac[3] predicted that electrons should also be diffracted by a standing light wave[4]. This Kapitza–Dirac effect is analogous to the diffraction of light by a grating, but with the roles of the wave and matter reversed. The electron and the light grating interact extremely weakly, via the 'ponderomotive potential'[5], so attempts to measure the Kapitza–Dirac effect had to wait for the development of the laser. The idea[6] that the underlying interaction with light is resonantly enhanced for electrons in an atom led to the observation[7] that atoms could be diffracted by a standing wave of light. Deflection of electrons by high-intensity laser light, which is also a consequence of the Kapitza–Dirac effect, has also been demonstrated[8]. But the coherent interference that characterizes wave diffraction has not hitherto been observed[9,10]. Here we report the diffraction of free electrons from a standing light wave—a realization of the Kapitza–Dirac effect as originally proposed.

In our experiment, an electron beam crosses two counter-propagating laser beams which form the standing wave light grating (Fig. 1). To reach sufficiently high laser intensities, we used a Nd:YAG laser with 10-ns pulses and an energy of 0.2 J per pulse focused to a beam waist 125 μm in diameter. Each counter-propagating laser beam travels an equal distance not differing by more than 1 mm. This is well within the coherence length of the laser beam (5 mm) where the standing wave is formed. A 380-eV electron beam is collimated by two 10-μm-wide molybdenum slits separated by 24 cm. A third slit cuts the height of the electron beam to the size of the laser beam waist. Subsequently, the electron beam crosses the standing wave about 1 cm after the third slit. A fourth 10-μm slit, 24 cm downstream from the interaction region, is used to scan the electron beam profile. The measured spatial width (full-width at half-maximum, FWHM) of the electron beam is 25 μm. This is a considerably narrower width than the expected distance between the zero and first diffraction order, $55\,\mu m = 2\lambda_{dB}/\lambda_{opt}\,(\times 24\,cm)$, where λ_{dB} is the de Broglie wavelength of the electrons and λ_{opt} is the wavelength of the laser light, 532 nm. We may thus expect the diffraction peaks to be resolved. The factor of two takes into account the ratio between the light grating periodicity and the light wavelength. The electrons are detected as a function of time with an electron multiplier. Each laser pulse is used as a start signal, and the detection of electrons is used as the stop signal for a time to amplitude converter. A multi-channel scaler records the pulses from the converter into coincidence time spectra. From the time spectra taken at various positions, the diffraction pattern is obtained directly.

The diffraction pattern is shown in Fig. 2. The diffraction orders are clearly resolved and fall at their expected positions ($n \times 55\,\mu m$, $n = 0, \pm 1, \pm 2, \ldots$). The heights of the diffraction peaks might be expected to be given by the analytic solution of the Schrödinger equation in the diffractive limit[11]. However, this is not the case. Given that some electrons pass through less intense regions of the focused laser beam and some electrons pass through more intense regions, a numerical solution of the Schrödinger equation gives acceptable agreement with the experimental data (Fig. 2). The parameters used in the numerical simulation (laser focus, 125 μm; laser intensity in the standing wave, $5 \times 10^{14}\,W\,m^{-2}$; electron velocity, $1.1 \times 10^{7}\,m\,s^{-1}$; optics transmission, 70%; overlap, 45 μm) are consistent with the experimental parameters. An overlap of 45 μm indicates the FWHM of the height of the standing wave. We calculate that with perfect overlap (standing wave FWHM of 125 μm) between the two counter-propagating laser beams, a laser light intensity ten times lower would yield a comparable diffraction pattern. The small asymmetry in the diffraction pattern (somewhat larger in the experiment than in the simulation) is attributed to a misalignment of the electron beam of approximately 1 mrad with respect to the laser and is indicative of the onset of Bragg scattering.

In some early experiments[12–15] attempts were made to measure the deflection of free electrons due to a light wave. Two experiments reported an effect[12,13], while two others did not[14,15]. Regardless of this controversy no diffraction peaks were observed. Indeed, recent reviews state that the Kapitza–Dirac effect has not been observed for electrons[9,10]. Explanations were offered to account for the controversy of the early experiments. Schwartz[16] has suggested that in two experiments the interaction strength was accidentally such that the height of the first-order diffraction peak was at a minimum. Considering the experimental difficulty of obtaining uniform laser intensity, this explanation seems unlikely. Fedorov[17], on the other hand, has suggested that a slow adiabatic turn-on is the main reason for the previous failure to observe the deflection owing to the 'ponderomotive potential'. In agreement with Fedorov, our simulation also shows that increasing the laser beam spatial width causes the Kapitza–Dirac effect to vanish for finite-sized electron beams. We have kept Fedorov's suggestion in mind while designing this experiment. Additionally, the greater stability and reliability of modern lasers and the improved performance of electronics have aided this experiment compared to earlier attempts to observe the Kapitza–Dirac effect.

Our results demonstrate that no fundamental problems stood in the way of observing the effect. At much higher laser intensities the important 1988 experiment[8] by Bucksbaum *et al.* showed that electrons could be deflected by the ponderomotive potential. Bucksbaum observed two classical rainbow scattering peaks separated by about 1,000 photon recoils. We observe quantum mechanical diffraction peaks separated by two photon recoils. An important difference between these experiments is that the rainbow peaks are not coherent, whereas diffraction peaks are coherent.

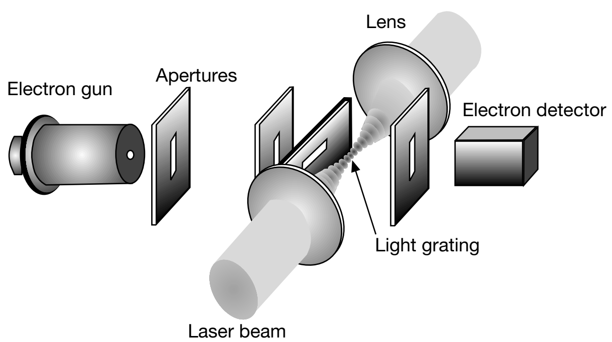

Figure 1 Schematic of our apparatus. Electrons are collimated by four molybdenum slits and diffract from a standing wave of light formed by two counter-propagating laser beams. The electrons must be described by a quantum mechanical wave while the standing light wave acts as a grating.

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The observation of the Kapitza–Dirac effect opens the door to various new experiments. Because the diffracted electron beams are coherent with each other, the Kapitza–Dirac effect constitutes a coherent beam splitter. Just as for atoms, the combination of three such beam splitters can be used to construct a Mach–Zehnder interferometer[18]. Compared to biprism electron interferometers, this new type of electron interferometer would operate at very low electron energies and seems to be well suited to study, for example, forward electron–atom scattering phase shifts[19]. Instead of using three consecutive beam splitters, it may also be possible to use the coherence of the diffraction pattern itself. When I_2 molecules are placed in a YAG laser beam (with experimental parameters almost identical to those used in our experiment) they will be aligned along the laser polarization axis[20,21], but only at the antinodes of the standing wave. The result is that the periodically aligned I_2 molecules will write a sinusoidal phase shift on the incoming electron waves. This shift will modify the diffraction pattern and could be used to monitor the I_2 alignment as it is influenced by, for example, molecular dissociation or ionization.

Apart from the use of the Kapitza–Dirac effect as a tool, it is interesting to study in itself. It has been shown experimentally that atoms moving through a standing light wave represent an example of classical and quantum chaos. The largest angles to which atoms can be deflected are determined by the boundary between regular and chaotic motion[22], and shaking the standing wave back and forth leads to the observation of Anderson localization[23]. Our experiment shows that the same experimental regime can be reached for electrons. The charge of the electron affords a convenient means of studying the effect of external interactions on quantum chaotic behaviour.

Increasing the laser intensity to 10^{15} W cm^{-2} (which is readily achieved in 100-ps pulse Nd:YAG lasers[24]) will raise the strength of the magnetic field of the laser beam to the extent that the electron spin would rotate by 180° in such a field. The question thus arises of whether the electron spin in the diffraction process could flip. Although classical arguments for a circularly polarized travelling wave seem to rule out this possibility[24], this question, in general, and in particular for standing waves, is to our knowledge unanswered. The atom optics counterpart of this effect is the "optical Stern–Gerlach effect" and has been observed[25]. However, this result cannot easily be extended to free electrons owing to the half-integer value of the spin. A spin flip in combination with diffraction would constitute a polarizing beam splitter for free electrons or, in other words, a microscopic Stern–Gerlach magnet. We have to keep in mind that Stern–Gerlach magnets for free electrons do not exist[26]. By increasing the laser intensity further to 10^{18} W cm^{-2} (for a laser wavelength of 1 μm), it is interesting to note that electrons are so light that relativistic speeds can be reached[24]. Thus the study of the interaction of free electrons with laser light can probably be extended from quantum mechanics to include spin, chaotic behaviour and relativistic mechanics. □

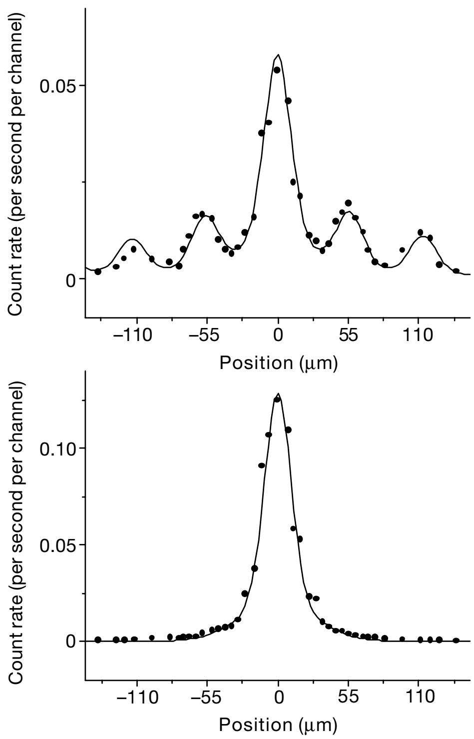

Figure 2 Experimental data. The electron detection rate is presented as a function of detector position. Our data (black points) agree reasonably well with a numerical solution of the Schrödinger equation (described in the text) and clearly show diffraction peaks, which is the signature of the Kapitza–Dirac effect. The bottom figure shows the electron beam profile with the laser beams turned off.

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