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Particles driven to diffraction

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Almost 70 years after it was first proposed, an experiment shows that electrons can be diffracted by light waves. This result highlights the interchangeable roles of matter and light.

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Wave-particle duality is the concept that all particles can behave as waves, and vice versa. This intellectually challenging notion, which is a fundamental prediction of quantum theory, has been tested in a new way by Herman Batelaan and co-workers, in an experiment reported on page 142 of this issue[1].

The debate over the particle versus wave character of light is far older than quantum theory. Newton was an early and active advocate for the corpuscular nature of light. But it was in the first decades of the twentieth century that quantum mechanics brought this discussion to a new plane by including matter as just another form of energy subject to the wave-particle dichotomy.

What does it mean to say that matter behaves like a wave? We know waves have ripples but, because atoms and electrons are so small, if they are waves then their ripples must be tiny. The quantum ripples of an electron in an atom are typically less than an ångström, or one ten-billionth of a metre, in size. But we don't need to see ripples to detect waves. The accepted evidence for wave-like behaviour is the phenomenon of diffraction.

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Diffraction of light forms a rainbow pattern on the surface of a compact disk.

Diffraction is easy to demonstrate for light. The rainbow pattern of colours that you see when you look at the surface of a compact disk is caused by light waves diffracting from the regularly spaced bands of shiny material that make up the tracks. This effect can be seen because the wavelength of light, although small, is large enough to be comparable to the spaces between adjacent tracks.

When light from a lamp or the sun strikes a compact disk, each component of colour in the 'white' light is deflected in a direction dictated by the ratio of its wavelength to the track spacing. Specifically, for light with wavelength λ incident at 90° on a grating with track spacing d, diffraction occurs at an angle given by $\sin\theta = \lambda/d, 2\lambda/d, 3\lambda/d$ and so on. Light waves scattering from all of the tracks add coherently only at these special angles. The wavelengths of visible light are tiny (just 400–700 nanometres) but, if the grating spacing d is small enough, the separation of the colours (due to the angle θ) is easy to detect.

Wave–particle duality in quantum mechanics means that we should be able to perform the same observation as described in the previous paragraph, even when the light waves are replaced by particles and the material grating by light. Think about how to make that compact disk out of a light beam for a moment. Don't panic if you haven't come up with a solution; the Batelaan group[1] has done it for you.

Batelaan and colleagues used a method originally proposed by two brilliant physicists, Paul Dirac and P. L. Kapitza, in a classic paper[2] written in 1933. Dirac and Kapitza each won Nobel prizes later, but not for this work. This is the only paper that they wrote together, and it seems to be an isolated curiosity. It was not written to resolve the wave-particle debate, because by the early 1930s this had been decided by numerous experiments in favour of... well, both particles and waves, as quantum theory predicts. Nonetheless they wrote that the diffraction of electrons by light would be a very interesting experiment.

The figure in the Kapitza–Dirac paper reveals the trick for creating a regular lattice of optical radiation (Fig. 1). Kapitza and Dirac reasoned that an optical standing wave would have the correct properties. A standing wave is just wave-like motion that oscillates but doesn't travel, such as the oscillations of a vibrating violin string. An optical standing wave has an oscillating electric field made by two counterpropagating and overlapping light beams. Kapitza and Dirac suggested that a standing wave of light could be constructed from radiation produced by mercury atoms in an arc lamp, which fluoresce in intense and sharp wavelength bands. If you use a compact disk to diffract light from a fluorescent lamp, you should be able to see the diffraction lines they were thinking about, because most fluorescent lamps produce their light from mercury atoms.

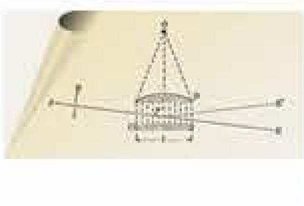

Figure 1: Making light of the matter.

A drawing from Kapitza and Dirac's 1933 paper[2] that describes a proposed method for the diffraction of electrons (from the path AE to AE') from an optical standing wave formed by a light source, O, a collimating lens, D, and a mirror, C. Batelaan and co-workers[1] use a similar geometry in their experiment.

High resolution image and legend (18K)

An electron beam in which the electrons follow parallel paths (are collimated) and have similar velocities would diffract from the standing wave at angles given by the same formulae that describe the diffraction of light from a grating — that is, at an angle determined by the ratio of the electron's wavelength to the period of the standing wave. (The period of the light grating is half the optical wavelength, because there are two intensity peaks per cycle in a standing wave.) The electron's quantum mechanical de Broglie wavelength, according to quantum theory, is inversely proportional to its momentum p: $\lambda_{\text{deBroglie}} = h/p$, where h is Planck's constant. So the angle of deviation for an electron beam incident at 90° should be integer multiples of $2h/(\lambda p)$, where λ is the wavelength of the light. This is one-hundredth of a degree or so for a grating of green light and electrons with 380 electron volts of energy, as in the Batelaan experiment.

But there is a problem: the force exerted by optical radiation on free electrons is incredibly weak. In other words, returning to our original experiment with the compact disk, it is as though the disk were nearly invisible because it was made of something with nearly the same optical properties as the air around it. In that case the light would pass right through it, and never diffract. This is why the Kapitza–Dirac thought experiment remained untested for many decades.

The situation improved following the invention of the laser. Continuous semiconductor diode lasers like the ones that read compact disks are still not powerful enough to demonstrate the Kapitza–Dirac effect for free electrons, but they can be used to diffract beams of atoms if their wavelength is close to an atomic transition line (like the spectral lines you get from fluorescent mercury atoms). Diffraction of matter waves by optical standing waves was therefore first demonstrated using a beam of neutral atoms passing through the optical standing wave of a continuous laser[3]. In this experiment, Gould, Ruff and Pritchard confirmed the Kapitza–Dirac formula, and in so doing helped to stimulate interest in the kind of particle–wave physics known today as atom optics. Techniques of atom optics have led to atomic Bose–Einstein condensates, atom lasers and developments in direct-write atom lithography.

The scattering force on free electrons by laser light is more than a billion times smaller than the carefully tuned laser–atom force, so the light has to be much more intense to have any effect. Continuous lasers simply cannot be made strong enough, but pulsed lasers can bridge this gap easily. The effect of light on free electrons was first observed[4] using large pulsed lasers in the 1960s, and it was studied in detail in the 1980s, partly by some experiments using standing waves[5]. These experiments did not use sufficiently collimated electrons to see the individual peaks at different angles that are the hallmark of electron diffraction from a standing wave. The full experimental test of this idea has had to wait until now, 40 years after the invention of the laser, and nearly 70 years since the Kapitza–Dirac paper.

Batelaan and colleagues' experiment[1] is well executed and the series of electron peaks at different scattering angles seen in Fig. 2 on page 143 is in beautiful agreement with the Kapitza–Dirac theory. A larger question, though, is where this advance leads us in physics. Batelaan's group proposes using it as a spectroscopic tool, or using the multiple peaks to build electron interferometers. These ideas are worth pursuing. They belong to a new field of physical research devoted to manipulating quantum phenomena using the exquisite control we now have over laser fields. Quantum computing, slow light, atom lasers and similar subjects that have appeared in these pages in the recent past belong to this new field of quantum control. The Batelaan experiment helps to tie these new advances to the foundations of quantum theory.

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