

but not all of them. Significantly, Alexander's latest and best PES model, which takes a supercomputer one month to compute, did a better job of fitting the data than his previous version. Correctly predicting the rotational features in the DCS is clearly a sensitive test of PES models.

Change or conserve

In their experiments, Kohguchi and Suzuki looked at two different types of inelastic collision: ones that either change or conserve NO's total electronic angular momentum Ω .

In the ground state, the spin and orbital angular momentum of the unpaired electron point in opposite directions, so $\Omega = 1/2$. In the next highest state, the two momenta are aligned, so $\Omega = 3/2$. After a collision, an NO molecule could end up in either state, with any of the allowed values of total angular momentum j (which, along with Ω , includes the

rotational angular momentum of the O and N nuclei).

Kohguchi and Suzuki measured the DCS for $\Delta\Omega = 0$ collisions at 11 different values of j and $\Delta\Omega = 1$ collisions at 9 different values of j .

The measured DCS varies considerably with final angular momentum state. But the experiments also show various features. At $j = 7.5$, for instance, the DCS has three peaks—at deflection angles of about 40° , 70° , and 110° .

As with the rotation data, predicting these and other features of the experimental data requires rigorous quantum mechanical treatment of the scattering. Alexander's latest PES, coupled with HIBRIDON, can match Kohguchi and Suzuki's data in most cases. But the combination doesn't succeed completely. Discernable discrepancies occur for $\Delta\Omega = 1$ and the medium-sized j values of 5.5 to 8.5. The extreme sensitivity of the

model to the difference between the A' and A'' surfaces could be the culprit.

Alexander sees evidence that varying the NO bond separation in his models might account for discrepancies. That suggestion is puzzling because exciting NO's lowest vibrational state requires 233 meV—far more than the 64 meV available in the collisions Kohguchi and Suzuki measured.

Whether they play a role in low-energy scattering collisions or not, vibrations, and the complications they bring with them, must be incorporated into the next step in this enterprise: predicting the outcomes of collisions that transform their participants chemically.

CHARLES DAY

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Electron Diffraction by Light, Envisioned 70 Years Ago, Is Observed at Last

Louis de Broglie's 1923 proposal that particles could display wave behavior paved the way to modern quantum mechanics. Within five years, Clinton Davisson and Lester Germer in the US, and George Thomson in Scotland, confirmed de Broglie's proposal by diffracting electrons off crystals. In 1933, Peter Kapitza and Paul Dirac proposed that a grating of standing waves of light could also diffract electrons: The diffraction peak separation would be proportional to the de Broglie wavelength of the electrons and inversely proportional to the wavelength of the light making the standing waves.

Kapitza–Dirac diffraction does not change the electron's energy. This diffraction contrasts with the more familiar Compton scattering, in which an electron gains energy by interacting with a single photon. The diffraction predicted by Kapitza and Dirac arises through electrons interacting, by virtual absorption and stimulated emission, with an even number of photons.

The interaction is sufficiently weak that it could not be tested with the technology available in 1933: One needs pulsed lasers to get the requisite light intensity. In 1968, Lawrence Bartell and coworkers successfully scattered free electrons off standing light waves, and 20 years later, while at Bell Labs, Philip Bucksbaum and colleagues studied the scattering in

A fundamental quantum effect involving the feeble interaction of light with free electrons requires intense lasers for its experimental realization. But that's just part of the story.

detail.¹ Until recently, however, no one had observed the coherent diffraction peaks that characterize the Kapitza–Dirac effect.

Now, at last, Herman Batelaan, Daniel Freimund, and Kayvan Afla-

tooni, working at the University of Nebraska–Lincoln, have observed coherent diffraction.² “This has been a long time coming,” commented David Pritchard of MIT, who led a team that observed a similar diffraction of neutral sodium atoms in the mid-1980s.³ “And it's really nice to see a definitive result.”

The heart of the Nebraska group's experimental setup is shown in figure 1. After a pulsed laser beam is split, the resulting two beams are redirected so that they approach a pair of

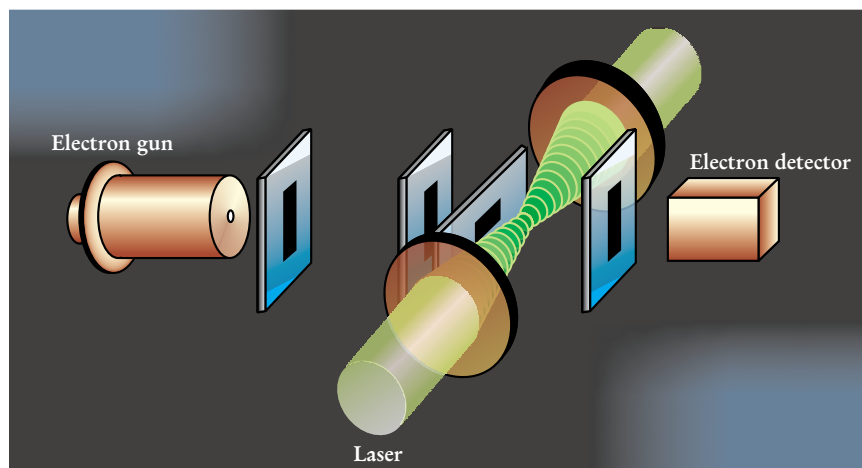


FIGURE 1. EXPERIMENTAL DESIGN to observe the Kapitza–Dirac effect. Counter-propagating laser beams combine to give a standing wave (green). Three slits focus the approaching electron beam. A fourth slit, downline from the interaction region, defines the detection direction. (Adapted from ref. 2.)

lenses from opposite directions. The lenses focus the counter-propagating pulses to a diameter of $125\text{ }\mu\text{m}$. The total path lengths of the beams differ by no more than 1 mm, significantly less than the 5-mm coherence length of the laser, so that the light beams superpose to create a standing wave.

The electron beam passes through three slits before encountering the standing wave. Two vertical slits yield a beam whose full width at half-maximum is $25\text{ }\mu\text{m}$, while the third slit, a horizontal one, cuts the height of the beam down to that of the laser beam focus. The directions in which electrons emerge from the interaction region are measured with the help of a movable slit that is downstream from the laser. In any given trial, the position of the final slit is fixed, but over the course of several trials, the slit position is moved; electrons that pass through it are counted by the electron detector.

Figure 2 shows the experimental result, a series of diffraction peaks separated by $55\text{ }\mu\text{m}$ —just as one would expect, given the experimental parameters. The heights of the peaks are also in good agreement with theory, although the electron intensities are difficult to calculate. That's because some electrons pass through hot spots in the focus of the laser beam, while others do not. Batelaan and company solved the Schrödinger equation numerically to obtain the theoretical curve indicated in the figure. The experimental data show a slight asymmetry, which the Batelaan group attributes to an electron beam that was not quite perpendicular to the laser beam. The asymmetry also appears in the numerical solution, which included the electron beam's approach angle as an adjustable parameter.

What took so long?

A key reason the Kapitza–Dirac effect was so difficult to verify experimentally is the weak interaction of free electrons with the electromagnetic field of light. One needs the intense light of pulsed lasers to have any chance to see the effect.

The Nebraska group's laser deposited 0.2 J in each of its 10-ns bursts. Although lasers can readily create pulses whose durations are shorter than 10 ns, the Batelaan group chose a more relaxed pulse length to increase the chance that the laser would be on when electrons crossed the interaction region, while

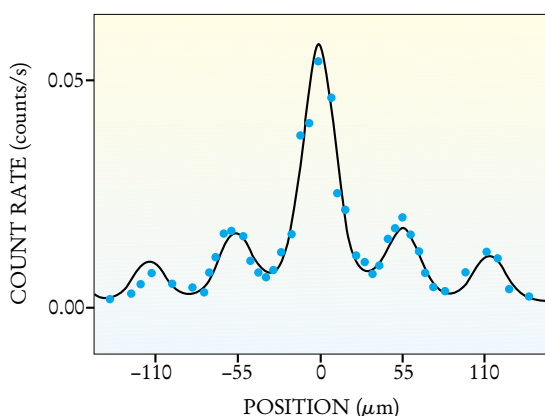


FIGURE 2. DIFFRACTION PATTERN of electrons by a standing light wave, giving well-defined peaks. The dependence of electron detection rate (blue dots) on detector position is in good agreement with a numerical calculation (black curve). The width of the diffraction peaks reflects the $25\text{-}\mu\text{m}$ width of the incoming electron beam. (Adapted from ref. 2.)

still giving a high enough intensity for electrons and photons to interact.

In addition to being intense, the laser has to be well focused, a point emphasized in 1974 by Mikhail Fedorov of Moscow's General Physics Institute.⁴ If electrons take too long to cross the light beam, diffraction cannot be observed unless the electron beam is collimated beyond what is experimentally possible. Batelaan noted that increasing the width of the laser beam in his simulations caused the Kapitza–Dirac effect to disappear.

The electron beam must also be well focused so that the diffraction peaks can be resolved. The Nebraska group experimented with beam-defining slits of various sizes and materials before deciding that $10\text{-}\mu\text{m}$ -wide, acid-treated molybdenum slits worked best. In intermediate trials, $5\text{-}\mu\text{m}$ -wide slits introduced lensing effects that reduced the quality of the emerging electron beam. The experimenters admit they don't fully understand the physics behind either the lensing effects or the superior performance of the acid-treated Mo slits.

There is precedent for the Batelaan group's work. Pritchard's work with sodium atoms, done in collaboration with Phillip Gould (University of Connecticut) and George Ruff (Bates College), used a continuous laser whose photon energy was near one of sodium's atomic transitions. The near resonance of the laser light greatly enhanced the strength of the interaction between the atoms and

light: The cross section in the MIT experiment was more than a billion times greater than that for electron–light interaction.

Bucksbaum (now at the University of Michigan), Douglas Schumacher (Ohio State University), and Mark Bashkansky (Naval Research Laboratory) studied in detail the scattering of electrons off laser light.¹ Working at Bell Labs, they used lasers a good 100–1000 times more intense than Batelaan's, having a pulse width of about 0.1 ns. Such short pulses are not amenable to interaction with electrons in a beam. Rather, Bucksbaum and company used their lasers to ionize a rare gas, creating electrons in the laser focus; they reported seeing broad scattering peaks. The scattering observed by Bucksbaum's group can be explained with a classical picture in which electrons are jostled about the oscillating potential associated with the standing electromagnetic wave before they are ejected from the interaction region.

Bucksbaum and company were unable to resolve single quantum-scattering features. The maximum of their electron-intensity distribution corresponded to scattered electrons absorbing the momentum carried by about 1000 laser photons, reflecting the enormous intensity of their lasers. The width of the peaks corresponded to about 100 photons' worth of transferred momentum. The resolution of individual peaks, reflecting the interaction of electrons with small numbers of photons, had to wait another 13 years for the Batelaan group's experiment.

A new regime

A number of potential applications exist for light gratings that can diffract electrons in a controlled way. Standing-wave light gratings, for example, could be used to explore features of quantum chaos. Mark Raizen (University of Texas) and coworkers diffracted neutral atoms with a light grating that was allowed to oscillate.⁵ They observed certain predicted irregularities—signatures of quantum chaos—in the diffraction pattern when the grating was shaken in just the right way. That study may be extendable to electrons, whose charge allows additional interactions to be thrown into the mix.

A light grating, suggests Batelaan, could be a key component in a device that can separate electrons by spin. In the Batelaan and Bucksbaum experiments, scattering electrons interacted

with an even number of photons. To satisfy angular-momentum conservation, then, the spin orientations of the incoming and diffracted spin- $1/2$ electrons had to be the same. Batelaan noted, however, that things are different if electrons encounter two counterpropagating, suitably polarized lasers, one of whose wavelength is half that of the other. In that case, electrons can flip their spins by interacting with an odd number of photons. Electrons whose spins are flipped up receive momentum kicks in the opposite direction to those whose spins are flipped down.

Light gratings split electron beams coherently, and it may be possible to use them as splitting, bending, and recombining elements for an electron interferometer. Electron interferometers are not new, but the interferometers currently being used split electron beams of higher energies than those used by the Nebraska group. The lower energies allowed by light gratings would provide physicists with greater sensitivity to a variety of interactions, such as electron-atom forward scattering or the interactions of electrons with metallic surfaces.

The applications just described may not come to fruition. The experimental parameters that yield clean electron diffraction patterns are not suited to studying quantum chaos with electrons, and it remains to be seen if, for instance, relaxing the focus of the electron beam will allow for interesting studies. According to Batelaan, the spin separator he imagines may require prohibitively high laser intensities. But Mark Kasevich of Yale University notes that no one can predict how the field of quantum optics will evolve: Perhaps light gratings will see applications in quantum devices or in quantum computing. "We're weaving some kind of quilt," he explains, "and it's hard to know where the connections are going to be made in even five years. Bringing the energy down for the coherent optics is pushing things to a new regime."

STEVEN K. BLAU

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Gamble Pays Off at the Advanced Light Source

The workers below are lowering one of three new superconducting bending magnets into the beamline at Lawrence Berkeley National Laboratory's Advanced Light Source this past August. These new magnets have added hard x rays to the accelerator's offerings of synchrotron radiation beams. The demand for such x-ray sources has grown explosively in recent years, thanks primarily to work on protein crystallography.

The ALS was built more than a decade ago as a high-brightness synchrotron radiation facility optimized to operate in the vacuum ultraviolet (VUV) and soft x-ray spectral regions (with photon energies ranging from 10 eV to 1.5 keV). Providing such radiation is still the lab's main mission, and it currently serves 1000 users per year. Soon after the facility was completed, however, ALS designers had an idea of how they might add some higher energy beamlines (up to 40 keV) without sacrificing the accelerator's existing capabilities.

Synchrotron radiation is produced as bending magnets steer electrons around the curves of the storage ring. It can also be produced by inserting devices such as undulators or wigglers into some of the straight sections of the ring. (These devices cause electrons to wiggle back and forth and hence radiate.) The standard way to add a hard x-ray capability to an existing storage ring is to insert a high-field wiggler, but the number of straight sections available for that purpose at the ALS is very limited.

ALS designers proposed instead to produce hard x rays in bending magnets. The peak energy radiated by electrons as they curve through a magnetic field is proportional to the square of the electron energy and to the magnetic field. At the ALS, the beam energy is fixed at 1.9 GeV, so the designers suggested raising the maximum photon energy by increasing the field strength of the bending magnet. In place of three of the normal 1.3-T bending magnets used at the ALS for VUV or soft x-ray beams, they proposed three 5-T superconducting magnets to yield hard x-ray beams. The three "superbend" magnets, can feed 12 user beamlines.

How could such superbend magnets be incorporated into an existing storage ring with minimal reconfiguration? The chief constraint was one of space: The new 5-T magnets were not allowed to bend the circulating electron beam by more than 10° , the bending angle given to electrons by the magnets that were being replaced. Thus, each of the three new magnets, while four times stronger, was only one fourth as long.

After years of studying this plan, the Berkeley lab started its Superbend Project in 1998, with David Robin at the helm. By this past August, the team was ready to implement the retrofit. It was a gamble, though, because the superbend magnets had to be added without affecting the established performance of the accelerator in the VUV and soft x-ray regions. And the shutdown for retrofit work had to be short, to avoid interruption of the scheduled experiments.

The changeover was made in just two weeks, and the first experiment on one of the new hard x-ray beams began in early October. Experiments are being built on another five of the new beamlines, and proposals are being made for the remaining six. The higher-energy beams are brighter than those produced by the normal magnets, but not as bright as the undulator beams at Argonne National Laboratory's Advanced Photon Source, which was specifically designed for the higher-energy radiation. Still, said Robin, the size and flux of the new ALS beams are well suited to protein crystallography and other experiments.

BARBARA GOSS LEVI

