Scattering of Electrons by Intense Coherent Light

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(Received 17 October 1986)

We report the first direct observation of electron inelastic scattering from the ponderomotive potential of an intense laser pulse in vacuum. Electrons gained up to 0.2 eV when scattered from the temporal leading edge of a 1064-nm (1.165 eV), 140-psec laser pulse, and lost comparable amounts of energy when scattered from the trailing edge. When directed to the most intense part of the pulse, they were deflected out of the beam.

PACS numbers: 42.50.Vk

At very high light intensities electron-photon scattering is dominated by stimulated photon interactions known as ponderomotive effects. This was first recognized by Kaptiza and Dirac,[1] who suggested that an optical standing wave could cause Bragg scattering of electrons by stimulated Thomson scattering. After the advent of lasers, Kibble, Eberly, and others reexamined the problem, concluding that a continuous laser beam could form a repulsive potential for free electrons.[2-6] Kibble pointed out that for a short laser pulse, electrons may exchange energy with light in nonquantized amounts,[2] just as a surfer gains potential energy when lifted by a wave.

We have observed for the first time electron acceleration and deceleration produced by "surfing" on the leading and trailing temporal edge of a laser pulse in vacuum. A unique pulsed beam of electrons (80 psec duration) was used to study the ponderomotive potential of a short (140 psec), tightly focused, 1064-nm laser pulse at four electron energies between 0.54 and 4.18 eV. These observations agree with calculations based on the predictions of Kibble and others.[2-4]

Kapitza and Dirac adopted scattering formalism to derive the probability for the stimulated Thomson effect. However, in the regime of very high light intensity, the scattering rate is so great that a classical treatment is possible. In the classical limit, stimulated photon scattering is most easily understood by consideration of the change in the total energy of an electron that takes place in a coherent light field.[3] The classical wiggling motion of the electron in response to the electromagnetic field produces a time-averaged kinetic energy of

$$U(\mathbf{r},t)=2\pi e^2 I(\mathbf{r},t)/m_e c\omega^2. \quad (1)$$

Here e is the electron charge, m_e its mass, and I, ω, and c are the intensity, angular frequency, and speed of the light, respectively. In the full quantum theory, $U(\mathbf{r},t)$ is the increase in the electron self-energy due to stimulated scattering of photons.[5] In a classical relativistic theory, $U(\mathbf{r},t)/c^2$ is the relativistic increase in the mass of an electron with speed $v=[2U(\mathbf{r},t)/m_e]^{1/2}$, and the scattering can be shown to be the motion of a particle with a position- and time-dependent variable rest mass $m=m_e/(1-v^2/c^2)^{1/2}\approx m_e+U(\mathbf{r},t)/c^2$.[4] For our purposes, however, it suffices to consider a nonrelativistic free electron, in the presence of a nearly monochromatic classical radiation field described by a vector potential $\mathbf{A}(\mathbf{r},t)$. The Hamiltonian for this particle is

$$H=\frac{[\mathbf{p}-(e/c)\mathbf{A}]^2}{2m_e}=\frac{p^2}{2m_e}-\frac{e}{2m_e c}(\mathbf{p}\cdot\mathbf{A}+\mathbf{A}\cdot\mathbf{p})+\frac{e^2A^2}{2m_e c^2}. \quad (2)$$

The A^2 term is a positive-definite quantity equal to U on time average. This is an effective repulsive potential, the "ponderomotive" potential. For neodymium-doped yttrium aluminum garnet (Nd:YAlG), its strength is $1.1\times10^{-13}[I/(1\ \mathrm{W/cm^2})]$ eV. A tightly focused, high-powered Nd:YAlG laser can produce scattering potentials of many electronvolts, enough to repel completely a low-energy electron.

Apart from strength, ponderomotive potential scattering differs from spontaneous light scattering in several ways. Unlike radiation pressure or Compton scattering, the force exerted by the gradient of a ponderomotive potential is independent of laser beam polarization or propagation direction. If the laser intensity is steady (continuous-wave conditions), the force is conservative, and charged particles scatter elastically. If the field intensity varies with time, however, an illuminated electron changes total energy by

$$\delta E=\frac{\partial H(\mathbf{p},\mathbf{r},t)}{\partial t}\delta t=\frac{2\pi e^2}{m_e c\omega^2}\frac{\partial I(\mathbf{r},t)}{\partial t}\delta t, \quad (3)$$

i.e., by an amount equal to the ponderomotive potential change at its location. This energy change is not related to the light quantum of energy $\hbar\omega$. Rather, it is the result of stimulated scattering among radiation modes of slightly different frequency that are present in any time-varying pulse. The electron energy change is accompanied by a redistribution of the photons in each mode, so that total energy is conserved.

A short, tightly focused laser pulse is an excellent laboratory for studying these two effects. If the laser inten-

sity does not vary in time while electrons enter and leave the focus, elastic scattering occurs. This may be seen in very low-density laser-plasma experiments,[7] and possibly dominated early attempts to observe the Kaptiza-Dirac effect.[8] It was recently found to produce intensity-dependent angular distributions in multiphoton ionization of xenon.[9] On the other hand, if electrons cross the rising or falling temporal edge of a laser beam, they surf on the pulse, gaining or losing energy.[10] The present experiment was designed to study this effect.

The experiment took place within a magnetically and electrically shielded vacuum region (base pressure 4×10^{-9} Torr). Two focused, parallel, pulsed laser beams entered and exited through small holes in the shields. Both pulses were derived from a continuously mode-locked Nd:YAlG laser, amplified in a two-stage Nd:YAlG amplifier. One was a transform-limited, 140-psec (FWHM), 20-mJ pulse of circularly polarized 1064-nm radiation, focused to 12 μm in the middle of the shielded volume. This was the ponderomotive scattering potential, with peak potential energy of 8 eV. The second beam, a 3-mJ, 100-psec linearly polarized, 532-nm pulse, was focused to 8 μm in the same focal plane, but horizontally separated by 180 μm. The relative positions were maintained by means of a simple achromatic microscope that was continuously monitored during the experiment with a television camera. The chamber was seeded with a minute amount (10^{11} cm^{-3}) of xenon, which produced photoelectrons in the 532-nm laser focus via nonresonant multiphoton ionization. These traversed the 180-μm vacuum separation, and encountered the 1064-nm laser pulse (Fig. 1, inset). The arrival could be delayed or advanced by up to 1 nsec relative to the 1064-nm pulse by a variable optical delay. Electrons were detected by microchannel plates approximately 40 cm downstream, where their energies were analyzed by time of flight. The detector subtended 3°, in line to accept undeflected electrons.

The electron gun for this experiment needed to be small, collimated, short pulsed, nearly monoenergetic, precisely timed to the infrared laser, and able to produce electrons at several energies below 8 eV. We found that the photoelectron spectrum from 532-nm multiphoton ionization of xenon is nearly ideal[11] (see Fig. 1). The source size, pulse duration, and synchronization are set by the focus of the 532-nm laser pulse, and since light is made from the second harmonic of a portion of the 1064-nm pulse, there is virtually no time jitter. The angular distributions have a maximum along the laser polarization, permitting the electron beam to be pointed in any direction perpendicular to the propagation direction.

Possible contributions to the spectral width of the source are power broadening, Doppler broadening of the atom, ac Stark shifts of the parent atom and daughter ion, space-charge broadening, and nonconservative ponderomotive forces in the *green* laser focus, i.e., the very

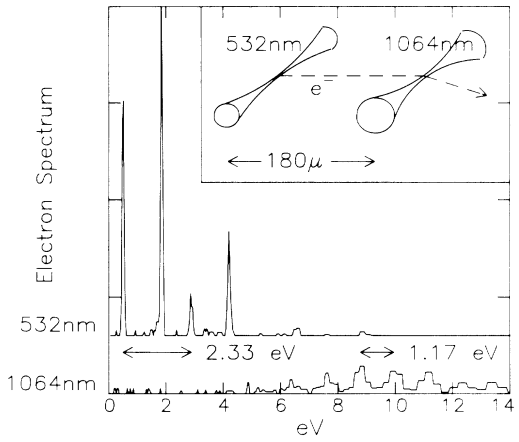

FIG. 1. Photoelectron spectra for xenon. Top trace: Multiphoton-ionization electron spectrum for 532-nm (2.33 eV) photons in xenon. These served as the electron gun in this experiment. Lower trace: spectrum from circularly polarized 1064-nm (1.17 eV) multiphoton ionization, with the same vertical scale as the top trace. These electrons were produced by the ponderomotive scattering potential, and were the principal source of background. The inset shows the scattering geometry.

effect we wish to study in the 1064-nm laser focus. All but the last are quite negligible. Ponderomotive forces are much smaller in the 532-nm laser beam because U scales as λ^2. The electron peaks were approximately 0.04 eV FWHM. The spectrometer resolution limit was 0.03 eV at 1 eV total energy, and increased as the square root of the electron energy.

The principal source of background electrons in this experiment was from multiphoton ionization of xenon in the 1064-nm laser focus. This was minimized by use of the recent discovery that circular polarization eliminates low-energy electrons from multiphoton ionization spectra at 1064 nm, as shown in Fig. 1.[12] By our employing circular polarization, the electron spectra below 5 eV consisted nearly entirely of electrons from the 532-nm laser.

Figure 2 shows several electron spectra with different time delays between the electron pulse and the ponderomotive pulse. Each trace contains 2000 laser shots collected at 10 Hz. The energy calibration was determined by our requiring that the peaks appear at the correct spectral position when the 1064-nm ponderomotive potential is absent. The four prominent peaks in each spectrum are identified as follows: six–532-nm-photon ionization to the $5p^5\,^2P_{1/2}$ state of Xe^+ at 0.54 eV; six photons to the $^2P_{3/2}$ state at 1.85 eV; and the seven-photon absorption processes to the same ion final states, at 2.9 and 4.2 eV.

The time listed to the left of each spectrum represents the relative delay between the moment of electron production and the peak of the ponderomotive potential at

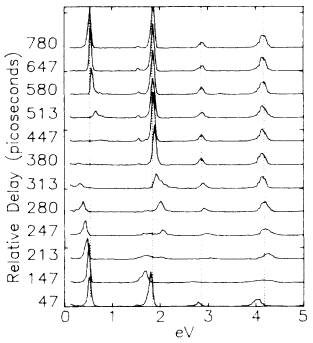

FIG. 2. Data. The experimental geometry is shown in Fig. 1. The numbers at left show the time advance between the 532-nm pulse and the 1064-nm pulse.

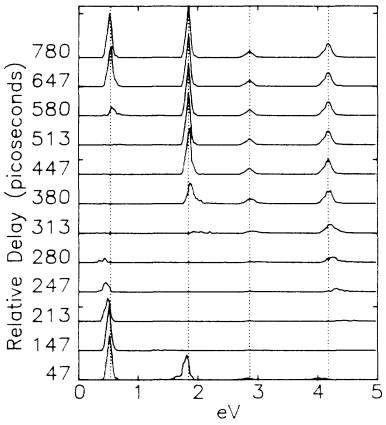

FIG. 3. Model calculation for the spectra of the 1064-nm laser pulse in the geometry of Fig. 1.

the focus 180 μm away. In the top trace, the electrons are produced well before the arrival of the peak ponderomotive potential. These electrons pass through the focus of the infrared laser before the light pulse arrives, so that their trajectories are unaffected, and their spectrum is essentially identical to the green-only spectrum in Fig. 1. As the time advance is reduced, displayed in the subsequent traces, the slowest electrons begin to experience the temporal leading edge of the laser pulse. In the data shown at 580 and 513 psec, the electrons have gained potential energy as the laser pulse overtakes them, which is partially converted to translational kinetic energy as they leave the pulse by sliding down the steep spatial gradient. The 447- and 380-psec spectra show the 0.54-eV electron beam nearly depleted by scattering from the 8-eV potential near the peak of the infrared pulse. At 313 psec advance, the electrons cross the temporal tail of the pulse, having decelerated by a process that is just the reverse of the acceleration observed at 250 psec advance. Finally when the time advance is reduced to nearly zero, the 0.54-eV spectrum returns to its unperturbed shape and position, since in this case electrons arrive at the infrared laser focus after the light pulse has passed. This spectrum is particularly important as a test for the absence of large space-charge forces near the focus, since these would continue to scatter electrons many nanoseconds after the laser pulse.

The scenario is repeated for the other peaks as well, but everything occurs at a shorter time advance, appropriate to the shorter delay for faster electrons to cross the 180-μm gap between the source and the potential.

We have compared the data to Monte Carlo–trajectory calculations involving a model ponderomotive potential and electron source. The model includes the following assumptions: (1) Both laser beams have Gaussian spatial and temporal profiles. (2) Measured values are used for the laser beam waists and pulse energies, the separation between the beams, and the initial electron energy and angular distributions. (3) The initial spatial and temporal distribution of electrons is determined from a model that includes a power-law ionization rate, saturation, and the effect of the ponderomotive potential in the 532-nm focus. (4) The electron trajectory is integrated forwards in time, by use of a Runge-Kutta technique. On each time step, the electron potential energy is reevaluated, and the electron motion calculated. In this way, both elastic and inelastic scattering are automatically included.

The agreement between the data and the trajectory calculations is seen in Fig. 3. The model reproduces the energy shifts, beam depletion, and line shapes observed in the experiment. Quantitative differences may indicate the need for a more sophisticated model of ionization in the 532-nm focus, such as the inclusion of deviations from a perfect Gaussian mode. This is under further investigation.

In summary, we have observed free-electron inelastic scattering from light in vacuum, caused by the time-dependent ponderomotive potential of an intense focused laser beam. In principle, this stimulated Thomson effect is capable of accelerating electrons to any energy up to the ponderomotive potential energy of the laser beam. Just as ponderomotive scattering of the photoelectrons contributes to distortion of the observed angular distributions,[9] the data presented here illustrate how the electron energy distributions, and particularly the widths of photoelectron peaks, may be broadened and shifted by the temporal inhomogeneity of the laser pulse.

We wish to thank M. Mittleman for early discussions that stimulated this research, and D. Schumacher for technical assistance. We particularly thank R. R. Freeman for extensive consultation and interest in all phases of this experiment. One of us (T.J.M.) acknowledges the partial support of National Science Foundation Grant No. CPE 81-19250.

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