Direct Observation of Multiphoton Processes in Laser-Induced Free-Free Transitions

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Multiphoton processes are detected in the scattering of electrons on argon atoms in the presence of a strong CO_2-laser field. The observations are in accordance with a recently developed semiclassical model.

We present here what we believe to be the first direct observation multiphoton absorptions and emissions by electrons in a strong laser field. Measurements were made in an electron-argon-atom scattering experiment in the field of a focused, pulsed CO_2 laser with a peak power of 50 MW. The following multiphoton absorption [Eq. (1)] and emission [Eq. (2)] processes were studied:

$$e^-(E_i)+\mathrm{Ar}+\mathrm{laser}\to e^-(E_i+nh\nu)+\mathrm{Ar}+\mathrm{laser}; \quad (1)$$

$$e^-(E_i)+\mathrm{Ar}+\mathrm{laser}\to e^-(E_i-nh\nu)+\mathrm{Ar}+\mathrm{laser}; \quad (2)$$

where E_i is the incident electron energy, $h\nu$ is the energy of a laser photon, and n can be any positive integer.

The one-photon ($n=1$) processes have recently been reported by Andrick and Langhans[1] using a 50-W continuous-wave CO_2 laser as a light source, which after focusing resulted in a flux density of 6×10^4 W/cm^2. At this flux density, a first-order perturbation expansion with respect to the laser field is suitable and provides in the soft-photon limit the following simple relation[2] between the one-photon absorption (emission) cross section $d\sigma_{ff}^{(1)}/d\Omega$ and the cross section without laser field $d\sigma_{el}/d\Omega$:

$$\frac{d\sigma_{ff}^{(1)}}{d\Omega}=\frac{p_f}{p_i}\Gamma^2\frac{d\sigma_{el}}{d\Omega}, \quad (3)$$

with Γ^2 given by

$$\Gamma^2=4.86\times10^{-13}\lambda^4FE_i\left[\frac{\vec{\epsilon}\cdot(\vec{p}_i-\vec{p}_f)}{2p_i}\right]^2, \quad (4)$$

where the laser wavelength λ is expressed in units of microns, the flux density F in units of watts per square centimeter, the incoming electron energy E_i in eV, and the polarization $\vec{\epsilon}$ is normalized according to $\vec{\epsilon}\cdot\vec{\epsilon}=1$ such that, for all incoming and outgoing electron momenta $\vec{p}_i$ and $\vec{p}_f$, the quantity in brackets in always between 0 and 1.

In the present experiment, however, flux densities in the order of at least $F=10^9$ W/cm^2 have been achieved in the scattering center. At these F values the quantity Γ^2 in Eq. (4) is about 50, which means that a perturbation expansion with respect to the laser field no longer applies and multiphoton processes are expected to contribute significantly. In the case of a CO_2 laser, however, a semiclassical soft-photon approach[3-5] can be applied, which yields the following cross-section formula for a free-free transition with a net absorption (emission) of n laser photons

$$\frac{d\sigma_{ff}^{(n)}}{d\Omega}=\frac{p_f}{p_i}J_n^2(2\Gamma)\frac{d\sigma_{el}}{d\Omega}. \quad (5)$$

Here $J_n(\Gamma)$ is the Bessel function of the first kind and order n, and Γ is given by Eq. (4). Clearly, if $|\Gamma|\ll1$ and $n=\pm1$, Eq. (5) reduces to Eq. (3), which shows the connection between the nonperturbative and the perturbative treatments of the laser field. From

$$J_0^2(x)+2\sum_{n=1}^{\infty}J_n^2(x)=1, \quad (6)$$

we note the sum rule ($n<0$ correspond to emissions; $n>0$ correspond to absorptions of a net number of $nh\nu$)

$$\sum_{n=-\infty}^{\infty}\frac{d\sigma^{(n)}}{d\Omega}=\frac{d\sigma_{el}}{d\Omega}, \quad (7)$$

which states that the various multiphoton contributions have to add up to the cross section without the laser field.

The experiment was performed in an electron spectrometer that has been described in the literature.[6] The CO_2 laser (Lumonics Model TEA-103-1) was shielded by a copper screen to reduce rf interference and the photon pulses of 2 μs duration were focused into the scattering center with a gold mirror ($R = 1$ m). The incident electron energy E_i was 11 eV and the scattered electrons were detected at an angle of 153° (with respect to E_i) and energy analyzed. The energy resolution of the spectrometer was 55 meV (full width at half-maximum). The photons were polarized so as to have $\vec{\epsilon}$ parallel to the momentum of the detected electrons, $\vec{p}_f$. The data were collected with two counting systems operated each with a gate that was triggered by a photon-drag detector. The first gate opening for 2 μs measured the scattered electrons in the presence of the laser field. The second gate opened with a delay of about 100 μs, i.e., long enough to ensure that the detecting system was counting the scattered electrons without laser field. To improve the statistics, the second gate remained open for 200 μs; however, we report here the counts for a 2-μs period so that we can compare it directly with the first counting system. This arrangement permitted us to measure directly the scattered electrons both with and without the laser field under the same experimental conditions.

The experimental results are shown in Fig. 1. Along the abscissa we give the energy of the detected electrons in units of laser-photon energies equal to 0.117 eV. On the ordinate we present the scattered-electron intensity collected in 600 laser pulses, each of a duration of 2 μs. Figure 1(a) shows the intensity of the elastically scattered electrons without the laser field. Figure 1(b) is a plot of the raw data showing the effect of the laser field on the scattered electrons. It produces a redistribution in energy of the original monoenergetic electrons. The one- and the two-photon processes are well resolved from the central peak demonstrating that, in fact, we detect well-defined quantum effects. We wish to emphasize here that to each experimental point marked with a circle on Fig. 1(a) there is a corresponding one on Fig. 1(b) that was determined under the same experimental conditions except for the laser field. The central peak of Fig. 1(b) shows a depletion of some 45%, and the intensities of the electrons that have gained and lost energy display a symmetrical pattern in accordance with Eq. (5) and as required by Eq. (7)—the area under the peaks adds up to the area under the peak without the laser field.

Detailed measurements of angular dependencies and energy variations with respect to resonances are in progress and will be published and compared with the theoretical analysis.

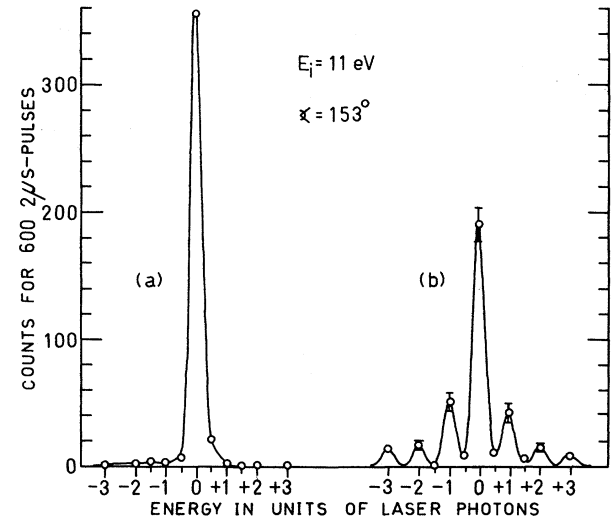

FIG. 1. Energy-loss spectrum of e^--Ar scattering. (a) Without laser field. The circles show the measured experimental points and the estimated outline of the process is drawn with a solid line, which was obtained by tracing out the elastic peak with a ratemeter and scaled to fit the maximum counts. (b) With laser field. The circles with error bars show the measured points and the estimated outline of the multiphoton (emission and absorption) processes are drawn in with solid lines obtained by scaling down the elastic peak as in (a).

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