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Absorption and emission of radiation during electron excitation of the $2\,^1S$ and $2\,^1P$ states of helium

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We are reporting electron spectra resulting from the inelastic scattering of 45-eV electrons from helium atoms through a scattering angle of 12° in the presence of an intense carbon-dioxide laser. The spectra presented are in the region of the $2\,^1S$ and $2\,^1P$ states of helium. These data show additional structure when the laser is present at scattered electron energies which correspond to an increase or decrease in electron kinetic energy of the equivalent of one laser quantum. These measurements demonstrate the simultaneous electron-photon excitation of an atom at high incident-electron energies.

Atoms are normally excited into higher states from their ground states through collisions with electrons or photons. Recently, however, it has been demonstrated that excitation can also occur through the "simultaneous" impact of an electron and one[1] or more[2,3] photons. This excitation mechanism may be described by

$$e^-(E_i)+(n+\nu)\hbar\omega+A \rightarrow A^*+n\hbar\omega+e^-(E_i+\nu\hbar\omega-E_{ex}), \quad (1)$$

where an electron of incident energy E_i is scattered from atom A in the presence of a laser, photon energy $\hbar\omega$, and emerges with energy $E_i+\nu\hbar\omega-E_{ex}$ after exciting the atom to a higher state, excitation energy E_{ex}. If the atom were to remain in its ground state then (1) would describe the so-called free-free transitions that have been studied for several years.[4]

Experimentally, the simultaneous electron-photon excitation (SEPE) process described by (1) has been studied for the excitation of the $2\,^3S$ state of helium through the detection of the metastable atoms at electron energies close to the threshold of excitation ($E_i \sim E_{ex}$). These data describe the total excitation cross section in the presence of the laser. Theoretically, however, excitation of the $2\,^1S$ state of hydrogen at high incident-electron energies ($E_i \gg E_{ex}$) has been considered.[5-8] Most of the results of such calculations have been concerned with the differential electron scattering cross sections, at small scattering angles, for electrons which emerge with energy equal to $E_i \pm \hbar\omega - E_{ex}$. For the conditions of these calculations exchange scattering could be ignored. The experiments, on the other hand, are examining an excitation which can only proceed through the exchange mechanism under conditions where the electron emerges with a low energy ($\sim\hbar\omega$). Comparisons between existing experimental data and theoretical predictions are therefore somewhat inappropriate. This Rapid Communication presents experimental results which were obtained under conditions which are much more closely related to those for the calculations. We have measured the scattered electron spectra after excitation of the $2\,^1P$ (21.218 eV) and $2\,^1S$ (20.616 eV) states of helium. The incident-electron energy for these measurements was 45 eV and the scattering angle was 12°.

The experimental arrangement is the same as that reported previously.[2,9] Radiation from a pulsed CO_2 laser operating in a multilongitudinal-mode optical configuration is focused into the scattering region of a conventional electron spectrometer, producing peak laser intensities in the 10^8-W cm^{-2} range. The laser beam, linearly polarized in the electron scattering plane, is brought in perpendicular to the incident-electron beam and the atomic beam. The atomic beam, formed by a pulsed supersonic beam valve, is incident at right angles to the electron scattering plane. The experimental spatial distribution of the laser energy and the overlap of the electron, atom, and laser beams are problems that we have discussed previously in the case of free-free transitions.[9,10] We expect that similar considerations also apply to the present experiments. In order to maintain a high scattered electron current the electron spectrometer was operated with a resolution of 70–75 meV for these measurements.

The incident-electron beam energy was fixed at 45 eV and the scattered electron energy analyzer set to collect electrons, scattered through 12°, that have energy corresponding to the excitation of one of the states of helium ($2\,^1S$ or $2\,^1P$). The scattered electrons were recorded with a counter which also simultaneously digitized and stored a small fraction of the laser pulse reflected from a sodium-chloride window on the spectrometer chamber. The laser was fired on alternate gas pulses so that at the end of a data run (5000 laser pulses) the accumulated data consisted of the sum of the laser pulses and the total electron counts recorded both with and without the laser. The data of interest were contained within a 2-μs window as this was the duration of the laser pulse. This procedure was then repeated for a range of scattered electron energies, in energy steps of $\frac{1}{4}\hbar\omega$, around the $2\,^1S$ and $2\,^1P$ states.

The electron spectrum, in the absence of the laser, showing peaks due to excitation to the $2\,^1S$ and $2\,^1P$ states is displayed at the top of Fig. 1. The position of the ^3P state is also indicated. The intensity of the dipole allowed transition to the $2\,^1P$ state is much higher than that to the $2\,^1S$ state as would be expected under the present experimental conditions. The effect of the laser on the electron spectrum is shown in the remaining diagrams in Fig. 1.

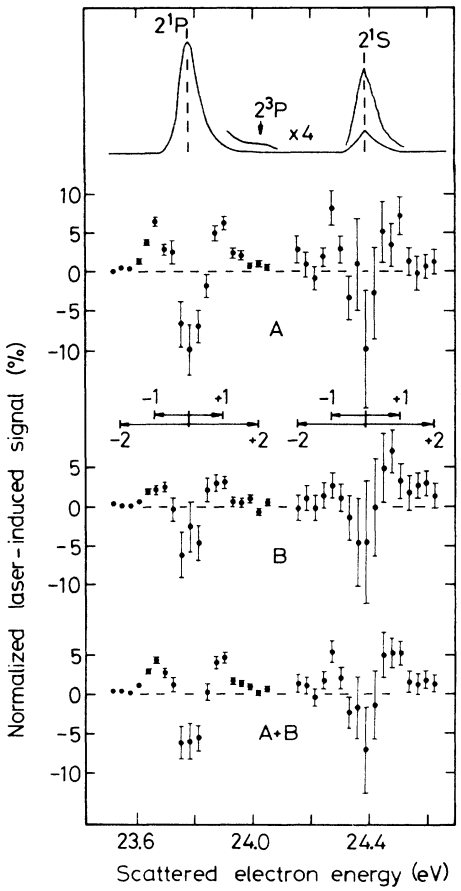

FIG. 1. The electron signal detected after scattering through 12° in the energy region of excitation of the $2\,^1P$ and $2\,^1S$ states of helium in the absence of the laser (upper) and the change in electron signal recorded when the laser is present through the first 1 μs of the laser pulse (A), the second 1 μs (B), and through the 2 μs ($A+B$). The change in electron signal has been normalized to the field-free signal at the excitation energy of either the $2\,^1P$ or $2\,^1S$ state. The electron energy, in units of laser quanta with respect to the excited states, is also indicated ($\pm 1, \pm 2$).

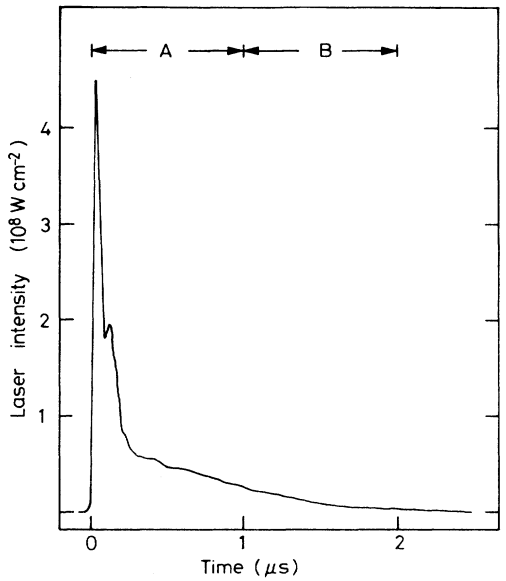

FIG. 2. A typical laser pulse showing the regions over which the change in electron signal is displayed in Fig. 1. The intensity is that estimated to be present in the scattering region at the center of the focal region.

These data are the recorded electron counts in the presence of the laser minus those in its absence normalized to the field-free count rate at the electron energy corresponding to the appropriate excitation, either $2\,^1P$ or $2\,^1S$, as a function of scattered electron energy for different time slices of the laser pulse as shown in Fig. 2. The spectrum labeled A represents that difference due to the first 1 μs of the laser pulse, containing the intense peak; B, the second μs, which contains most of the low-intensity tail; and $A+B$ is over the 2 μs. The field-free count rate used for normalizing the data is that for 1 μs for the first two spectra and for 2 μs for the bottom spectrum. This procedure allows the direct comparison of the influence of the laser for the two excitations and for the different average laser intensities. In all spectra, a decrease in cross section at the excitation energy and an increase at $\pm 1\hbar\omega$ are clearly seen. The data around the $2\,^1S$ excitation show a greater statistical uncertainty because of the much lower field-free excitation cross section. The peaks at $+1\hbar\omega$ represent the change in excitation cross section due to SEPE involving the absorption of one photon and those at $-1\hbar\omega$ involving the emission of one photon. These data are reminiscent of those published for elastic scattering of electrons from atoms[4] which showed a depletion in signal at the elastic peak with this loss in signal being distributed over the peaks due to the absorption and emission of photons, to satisfy an overall sum rule. Such a sum rule appears to be satisfied for the experiments reported here. The additional signal due to the laser at $\pm 1\hbar\omega$ represents $\sim$5% of the field-free signal with a depletion of $\sim$10% at the more intense part of the laser pulse.

The average laser intensity over part A of the laser pulse is 7×10^7 W cm^{-2}, while that over part B is approximately five times smaller. However, the additional signals recorded at $\pm\hbar\omega$, during the low-intensity tail of the laser pulse, are reduced by only a factor of 2 compared with those measured during the first part of the pulse. This suggests that the effects of the radiation are strongly nonlinear at high intensities similar to the behavior observed for free-free transitions[4,9,10] and it is surprising, therefore, that no signals are observed at $\pm 2\hbar\omega$ in Fig. 1, spectrum A.

Recent calculations[8] predict that, at high incident-electron energies and small scattering angles, differences in cross section between absorption and emission may be observed. These occur through the interference, either constructive or destructive, of the scattering amplitudes resulting from the laser interacting with the projectile electron and with the atom. At small scattering angles the two amplitudes are of similar magnitudes making interference effects particularly visible. The actual occurrence of such marked differences between absorption

and emission depends on such parameters as the laser intensity and polarization, the atom, the incident electron energy, etc., and requires detailed calculation of the scattering amplitudes. The data presented above demonstrate that we can now measure the differential scattering cross sections for SEPE of two states of helium at different incident-electron energies over a range of scattering angles (12° to 35° for the present experimental geometry). The differential cross sections could then provide a stringent test for the theory. We hope to report the results of these new measurements in the near future but detailed calculations for the excitation of the $2\,^1S$ and $2\,^1P$ states of helium in the field of a carbon-dioxide laser are also required.

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