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Laser-assisted elastic electron-atom collisions

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We report experimental measurements of electron spectra resulting from the scattering of 9.5-eV electrons by helium atoms through an angle of 9° in the presence of a high-intensity ($\sim 10^8$ W cm^{-2}) CO_2 laser. The intensities of the additional peaks which occur separated from the elastic scattering peak by multiples of the photon energy in the presence of the laser are much greater than expected. These data suggest that calculations based on the Kroll-Watson approximation, usually applied to this type of experiment, are inappropriate for these scattering conditions.

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The influence of intense electromagnetic radiation on the scattering of an electron by an atomic target has been studied quite extensively, both theoretically [1,2] and experimentally [3–6]. This interest stems from its relevance to applied fields such as laser heating of plasmas and to fundamental problems in collision physics. It is also now accepted [7] that there is a direct connection with the phenomena of above-threshold ionization [8] and multiphoton detachment of negative ions [9].

Much of the theoretical work has been based on the Kroll-Watson approximation, which was first introduced as a nonperturbative treatment for interaction of the laser field in the case of potential scattering [10,11]. In its application to scattering of electrons from real atoms in the presence of a low-frequency laser the interaction between the laser and atom is ignored. This leads to the rather simple result that the cross section for a scattering process in the presence of the laser may be expressed as the cross section in the absence of the laser modified by a term describing the laser-electron interaction. For example, for the case of "elastic" scattering of electrons where the electron's kinetic energy may change by multiples of the photon energy through absorption (emission) of photons from (to) the laser field (usually known as free-free transitions), one may deduce for the differential cross section for an n-photon process:

$$\frac{d\sigma_{FF}(n)}{d\Omega}=\frac{p_f}{p_i}J_n^2(\lambda)\frac{d\sigma_{\rm el}}{d\Omega}\ , \qquad (1)$$

with $\lambda^2=1.944\times10^{-12}\lambda_0^4F_0E_i(\boldsymbol{\epsilon}\cdot(\mathbf{p}_i-\mathbf{p}_f)/2p_i)^2$. $d\sigma_{\rm el}/d\Omega$ is the field-free elastic scattering cross section, $J_n(\lambda)$ is the Bessel function of the first kind and order n, λ_0 is the laser wavelength in micrometers, F_0 is the laser intensity in W cm^{-2}, E_i is the incident electron energy in eV, ϵ is the laser polarization, and $\mathbf{p}_i-\mathbf{p}_f$ is the change in electron momenta.

The range of applicability of Eq. (1) is not well known, but one should at least have $E_i \gg \hbar\omega$. The validity of the Kroll-Watson approach has been examined theoretically to some degree in recent years. At small scattering angles, where $d\sigma_{FF}(n)/d\Omega\sim 0$ from Eq. (1), it has been shown that the laser-atom interaction is not negligible even for quite moderate laser intensities and in many cases dominates the scattering process [12]. Also, at small scattering angles, with the laser polarization parallel to the incident electrons, a "channelling" of the scattering into small scattering angles has been predicted

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due to the "oscillatory" motion imposed on the electron by the electric field of the laser [13]. The influence of the laser field on the exchange scattering amplitude has also been considered [12,14] to some extent.

Experimentally, there has been no systematic study of the range of validity of the Kroll-Watson approximation, although there have been examples where departures from this simple approach are indicated [15,16]. We have now embarked on such a systematic study of elastic scattering, and this Rapid Communication presents the first data from this study which demonstrate convincing evidence for such departures. A full report will be presented in the near future.

Data are presented for low-energy scattering ($E_i = 9.5$ eV) of electrons from helium through 9° in the presence of a CO_2 laser ($\hbar\omega = 0.117$ eV), with intensities into the 10^8-W cm^{-2} range. The conditions for these experiments were chosen for several reasons. At an electron energy of 9.5 eV, the primary condition for application of (1), $E_i \gg \hbar\omega$, should be satisfied while minimizing the effect of the target's excited states, which lie at energies of ~ 19 eV and above. This would also be true at this electron energy for future studies of neon and argon. The dipole polarizability of helium is small and effects due to the laser-target interaction are expected to be small. Previous experimental work had also furnished reasons for this choice. Large backgrounds at small scattering angles ($\sim 20°$) were reported [17] in work on resonance excitation in free-free scattering from neon and argon at low laser intensities ($\sim 10^5$ W cm^{-2}), but small backgrounds

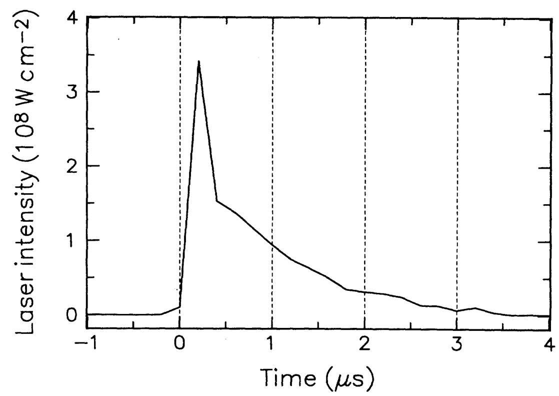

FIG. 2. A typical CO_2 laser pulse profile with the time periods for which data are presented in Fig. 1 as indicated.

were observed [5] for similar studies in helium and at much higher laser intensities [18]. This background was tentatively attributed to polarization of the atomic target at even such low laser intensities. We expected that these present experiments would provide "baseline" data for our systematic study of electron-atom scattering at small scattering angles in the presence of a laser.

The experimental arrangement is similar to that reported previously [15]. Radiation from a pulsed CO_2 laser operating in a multi-longitudinal-mode optical

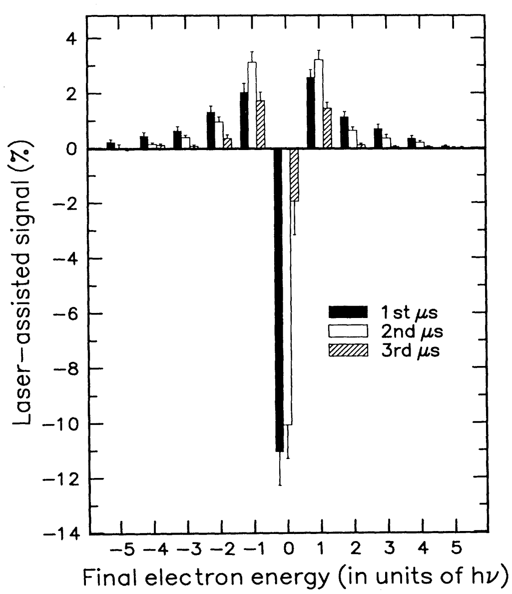

FIG. 1. Electron spectra resulting from elastically scattering 9.5-eV electrons from He through 9° in the presence of a CO_2 laser. The laser-assisted signal is the change in electron signal produced by the laser for each of the first three microseconds of the pulse, expressed as a percentage of the field-free elastic scattering signal. The energy scale for the final electron energy is in units of laser quanta (0.117 eV) with respect to the elastically scattered energy (9.5 eV). The error bars indicate one standard deviation.

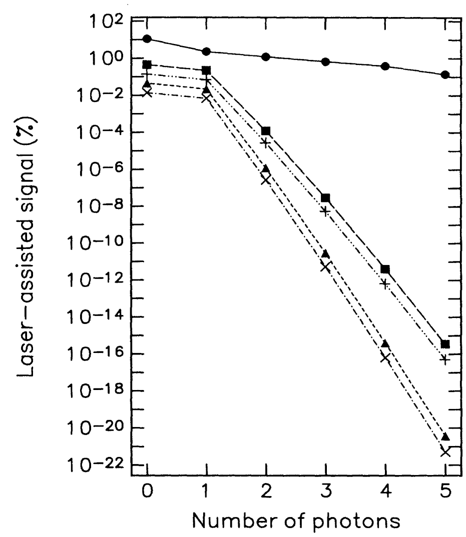

FIG. 3. Change in the electron signal due to the laser expressed as a percentage of the field-free elastic scattering signal for up to five photon processes as observed experimentally during the first microsecond of the laser pulse (—●—) and calculated from Eq. (1) assuming spatially homogeneous laser intensities of 1×10^8 W cm^{-2} (– –▲– –) and 1×10^9 W cm^{-2} (– –■– –) and a Gaussian distribution in the laser focus with maximum intensities of 1×10^8 W cm^{-2} (–·–·–×–·–·–) and 1×10^9 W cm^{-2} (–· · · –+– · · · –). The absolute value of the change in signal due to the laser is plotted since at $n=0$ there is a decrease in signal while an increase is expected and observed for $|n|>1$. The experimental points are the averages of the signals for absorption and emission for n photons displayed in Fig. 1.

TABLE I. Average laser intensities estimated from the measured energy of the laser pulse (experimental) and calculated from the measured electron spectra using the technique of Jung [20] for each of the three 1-μs periods of the laser pulse. The ratio of the sum of the measured increases in cross section for $|n|>0$ to the decrease in cross section at $n=0$ produced by the CO_2 laser are also given for each of these time periods.

	Average laser intensities ($W\,cm^{-2}$)		
Period of laser pulse	Experimental	Calculated	Sum rule ratio
First microsecond	1.5×10^{8}	1.0×10^{11}	0.85 ± 0.13
Second microsecond	6.4×10^{7}	5.5×10^{10}	0.89 ± 0.14
Third microsecond	2.2×10^{7}	1.8×10^{10}	1.95 ± 0.64

configuration is focused into the scattering region of an electron spectrometer, producing peak laser intensities in the 10^8-$W\,cm^{-2}$ range. The electron spectrometer and scattering chamber are, however, different from those used in our previous work, but full details will be reserved for a future publication. The linearly polarized laser beam is brought in perpendicular to the incident electron beam with its electric-field vector parallel to the incident electron direction. The atomic beam, formed by a pulsed supersonic beam valve, is incident at right angles to the scattering plane. In order to maintain a high scattered electron current, the electron spectrometer was operated with a resolution of ~50 meV for these measurements.

The electron-beam energy was fixed at 9.5 eV and the scattered electron-energy analyzer set to collect electrons elastically scattered through 9°. The detected 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 and focused into a photon-drag detector. At the end of a data run (5000–10 000 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 at 200-ns time intervals throughout the duration of the laser pulse. This procedure was repeated for scattered electron energies corresponding to the absorption and emission of up to five laser photons.

The effects of the laser on the electron spectrum are presented in Fig. 1 at different time intervals of the laser pulse (Fig. 2). These data are shown as the recorded electron counts in the presence of the laser minus those in its absence expressed as a percentage of the observed field-free count rate for elastic scattering. A decrease in cross section at the $n=0$ (elastic) scattering peak with increases in cross section at $|n|>0$ is clearly observed for each of the first three microseconds of the laser pulse. These data are similar to those published by Weingartshofer *et al.* [3,4], but with the change in signal relative to the field-free elastic signal being displayed rather than the number of electrons recorded. Measurements at $n=\pm\frac{1}{2}$, $\pm1\frac{1}{2}$, or with no electron beam, or no gas beam, etc., were also made in order to check for spurious signals.

In order to gauge whether any significant departures from the Kroll-Watson approximation are observed under the present experimental conditions, the results of simple calculations of this type are displayed in Fig. 3 for laser intensities of 1×10^8 $W\,cm^{-2}$ and 1×10^9 $W\,cm^{-2}$ together with the experimental data for $|n|$ up to 5. For the values of λ for these scattering conditions the results of the calculations are closely approximated by using the first term in the small argument expansions for the Bessel functions, i.e., $J_n(\lambda)=(\lambda/2)^n(1/n!)$, as can be seen by the simple power dependence on the laser intensity. The description of the laser resulting in Eq. (1) (single mode, spatially homogeneous, etc.) is a poor one for real lasers in real experiments. For comparison, the results from performing a Gaussian average over the laser focus are also shown in Fig. 3. This has the tendency to reduce the changes in cross section due to the laser, since many electrons now experience lower laser intensities for any particular peak intensity.

It can be clearly seen that the observed changes are much greater than those calculated, even if the effects of spatially averaging the laser intensity are ignored. It should also be pointed out that the effects of changing the model describing the laser (for example, a chaotic laser pulse [19]) are minimal when the arguments λ are so small.

The comparison of experimental data, such as that shown in Fig. 1, with the results of calculations has received much attention. For example, Jung [20] has proposed that the experimental data may be used to determine the average laser intensity experienced by the electrons. Application of these ideas, using the Kroll-Watson approach, to the data of Weingartshofer *et al.* at large scattering angles gave consistent results for the laser intensities [4]. However, for the data reported here, the laser intensities calculated in this way are orders of magnitude greater than one could reasonably expect for our laser (Table I). Incidentally, a similar discrepancy was previously observed [4] in the scattering of 15.8-eV electrons from argon through an angle of 8°, but was attributed at that time to a possible error in the measured scattering angle.

Implicit in the Kroll-Watson approximation is the sum rule

$$\sum_{n=-\infty}^{\infty}\frac{d\sigma_{FF}(n)}{d\Omega}=\frac{d\sigma_{\rm el}}{d\Omega}\ . \qquad (2)$$

The ratios of the total increase in signal for $|n|>0$ to the decrease in signal at $n=0$ due to the laser which should equal 1 according to (2) are also given in Table I. Unfortunately, it is not possible to say whether there are any significant departures or not from the sum rule from these data.

It is also interesting to note that in Fig. 1 the laser-assisted cross sections for both one-photon processes (absorption and emission) are significantly higher for the second microsecond of the laser pulse than the first microsecond, in contrast to all other n-photon processes. The average laser intensity estimated during this second microsecond ($\sim 6\times10^7$ W cm^{-2}) is much lower than that which includes the peak of the laser pulse. This indicates the one-photon cross sections go through a maximum at quite moderate laser intensities.

From the above considerations, we therefore have to conclude that the Kroll-Watson treatment is not appropriate for the conditions of these experiments. At higher electron energies ($\sim$19 eV) and 13° scattering angle, there seems to be better agreement [18]. If one now reconsiders the data of Andrick and Bader [5,17] from the viewpoint of the change in electron energy rather than the target atom, these data may also indicate serious disagreement with this approach at low ($\sim$11 eV) electron energies and small ($\sim$20°) scattering angles, even at low laser intensities ($\sim 10^5$ W cm^{-2}).

In order to examine this suggestion and to probe the validity of the Kroll-Watson approach, experiments over a range of scattering angles and electron energies and with different atomic targets are required. We are presently pursuing such a study and early indications are that the departures from the Kroll-Watson treatment are even larger at lower electron energies.

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