Inelastic scattering of quasifree electrons on O^{7+} projectiles

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Absolute doubly differential cross sections (DDCS's) for the resonant inelastic scattering of quasifree target electrons on H-like projectiles have been measured. Electron spectra for 20.25-MeV O^{7+} projectiles on an H_2 target were measured. The spectra contain a resonant contribution from the $3l3l'$ doubly excited states of O^{6+}, which decay predominantly to the $2l$ states of the O^{7+} via autoionization, and a nonresonant contribution from the direct excitation of the projectiles to the $O^{7+}(2l)$ state by the quasifree target electrons. Close-coupling R-matrix calculations for the inelastic scattering of free electrons on O^{7+} ions were performed. The relation between the electron-ion inelastic scattering calculation and the electron DDCS's for the ion-atom collision was established by using the inelastic scattering model (ISM). We found excellent agreement between the theoretical and measured resonant peak positions and relative peak heights. The calculated absolute double differential cross sections for the resonance processes are also in good agreement with the measured data. The implication is that collisions of highly charged ions on hydrogen can be used to obtain high-resolution, angle-resolved differential inelastic electron-scattering cross section. [S1050-2947(96)50212-X]

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The study of the interaction of electrons with highly charged ions is of great interest due to the significance of this process in high-temperature plasmas [1,2]. Ionization and recombination have been studied in crossed-beam and merged-electron-ion-beam experiments. Total cross sections can be measured in these experiments by looking at the charge changed ions [3–5]. In the case of merged-beam experiments performed in storage rings the effects of closely spaced resonances can be at least partially resolved due to the high-energy resolution in the cooled beams. Müller [3] recently reported on the current progress in electron-ion experiments in storage rings, which can provide total cross-section data for recombination and electron-impact ionization processes. Electron-beam ion trap and electron-beam ion source sources have also been used to study recombination and ionization through the observation of the product ion yields as well as the x-ray emission from excited-ion states [6,7]. Differential cross sections for electron-impact excitation of several singly charged ions have been measured by Chutjian and co-workers [4,5,8] using crossed-beam techniques. Dunn and co-workers [9,10] have investigated the angular scattering in electron-impact excitation of multiply charged ions using a merged-beam technique. A limited number of direct measurements of electron-impact excitation of ions have been done mainly due to the inherent limitations of performing merged- or crossed-beam experiments [11]. Absolute doubly differential electron production cross sections (DDCS's) for ion-atom scattering are readily available. We show that these cross sections can be directly related to electron-impact excitation of highly charged ions by using the inelastic scattering model (ISM).

Recently, Hvelplund *et al.* [12] reported a study of resonant inelastic scattering of quasifree electrons on C^{5+}. In this experiment, the ejected electron yield of the doubly excited $3l3l'$ autoionizing states of C^{4+} was measured. Bhalla *et al.* [13] successfully used the inelastic electron-scattering model to qualitatively reproduce the resonant structure observed by Hvelplund *et al.* [12]. Absolute doubly differential cross-section measurements of inelastic scattering of target electrons on H-like projectiles have not, to our knowledge, been reported to date.

It is the purpose of this Rapid Communication to report a direct comparison between the experimental and theoretical resonant inelastic electron scattering DDCS's for $1s \rightarrow 2s/2p$ excitation of $O^{7+}+H_2$ in the vicinity of the $3l3l'$ resonances. The validity of the ISM as it applies to the description of the resonant structure in inelastic ion-atom collisions is therefore examined in some detail.

Inelastic scattering of electrons from ions with one or more electrons exhibit rich resonant structure. These resonances are due to the formation of doubly excited states of the electron-ion compound system. The cross section for inelastic scattering as a function of incident electron energy should therefore consist of a smooth contribution due to the direct inelastic channel, a contribution from the resonance channel, and a contribution from the interference between these two channels.

When the projectile ion velocity V_p is much larger than the electron velocity the scattering of quasifree (loosely bound) electrons of a light target from a projectile ion can be related to the free-electron ion scattering by accounting for the momentum distribution of the target electron. Thus in the *projectile rest frame* the target electron has a continuous distribution of energies and the differential cross section for any ion-atom process (e.g., projectile excitation) $\partial\sigma/\partial\Omega$ can be described as the corresponding electron-ion cross section $(\partial\sigma/\partial\Omega)_e$ multiplied by the probability of having a target electron of the appropriate momentum summed over all electron momenta. This model has been referred to as the impulse approximation or the electron-scattering model [15–17]. The basic equation is

$$\frac{\partial\sigma}{\partial\Omega} = \int \left(\frac{\partial\sigma}{\partial\Omega}\right)_e |\psi(\mathbf{p})|^2 d\mathbf{p}, \tag{1}$$

where $\psi(\mathbf{p})$ is the target electron wave function in momen-

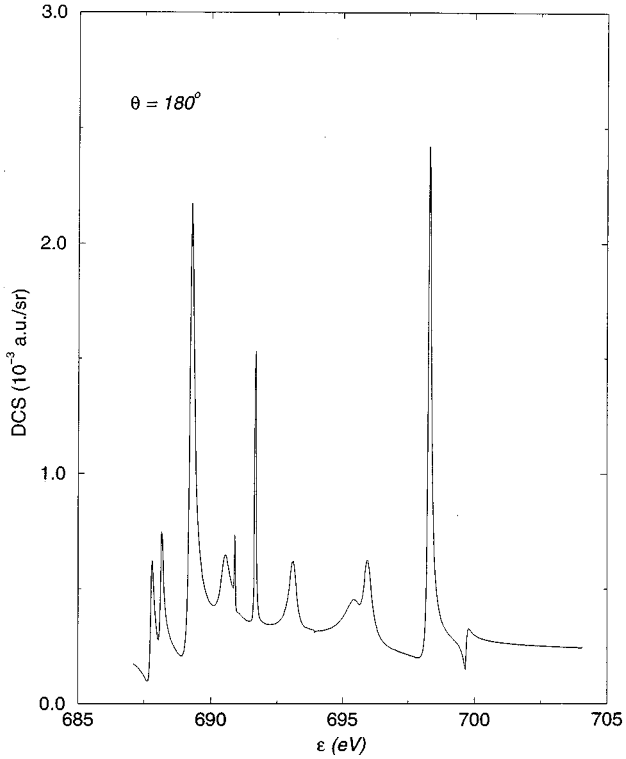

FIG. 1. Differential cross sections for $e^- + O^{7+}$ as a function of the incoming electron-impact energy at a scattering angle of 180° for the excitation from the $1s$ to $2s/2p$ states. In the center-of-mass frame the 180° scattering angle corresponds to the 0° observation angle in the ion-atom experiment. Note that the outgoing electron energy is equal to the energy of the incoming electron minus the excitation energy, 653.06 eV, of $1s$ to $2s/2p$.

tum space. For the case of inelastic electron scattering, Eq. (1) can be used to obtain the DDCS in the *projectile frame* as

$$\frac{\partial^2\sigma}{\partial\Omega\,\partial\epsilon} = \left(\frac{\partial\sigma}{\partial\Omega}\right)_e \left(\frac{J(Q)}{Q+V_p}\right), \tag{2}$$

where V_p is the velocity of the projectile and $Q = \sqrt{2}(\sqrt{\epsilon+E} - V_p)$. Here ϵ is the energy of the incident electron and E is the ionization energy of the target electron. The Compton profile of the target electrons $J(Q)$ represents the probability distribution of the target electron momentum (Q) along the collision direction. The experimental Compton profile [14] for H_2 can accurately be represented by the following formula:

$$J(Q) = \frac{a_1}{[1+(Q/k_1)^2]^3} + \frac{a_2}{[1+(Q/k_2)^2]^4}, \tag{3}$$

where $a_1 = 1.0012$, $a_2 = 0.5383$, $k_1 = 0.9896$, and $k_2 = 1.5566$.

The possible contribution to the excitation of the projectile by the target nucleus is ignored in the ISM because such contributions are expected to be only significant for low projectile velocities. The electron-ion differential cross sections (DCS's) were calculated from transition matrix elements, which are obtained from the R-matrix programs developed for the Opacity Project [18]. The transition matrix elements were calculated using the lowest 15 hydrogenic orbitals, up to $n=6$, to represent the target within the R-matrix internal region. The R-matrix boundary is taken at 13 a.u., and 40 continuum orbitals have been included in the expansion of the total wave function. All $(N+1)$-electron symmetries with even and odd parities up to total angular momentum $L=12$ were used. In order to calculate the DCS's appearing in Eq. (1), a program written by Bhalla *et al.* [13], which is similar to an earlier program of Salvini [19], has been used. The DCS for excitation from $1s \rightarrow 2s$ and $1s \rightarrow 2p$ have been calculated in an energy range from 687 to 704 eV with an energy mesh of 0.034 eV. In Fig. 1, the DCS's for $e + O^{7+}$ are plotted as a function of electron-impact energy at a scattering angle of 180° for excitation from $1s$ to $2s/2p$ states. The rich resonance structure observed in this energy region is associated with the population of the doubly excited $3l3l'$ states of O^{6+} that decay predominantly to $n=2$ via autoionization. The calculations clearly show pronounced Fano-type profiles, which are associated with the interference

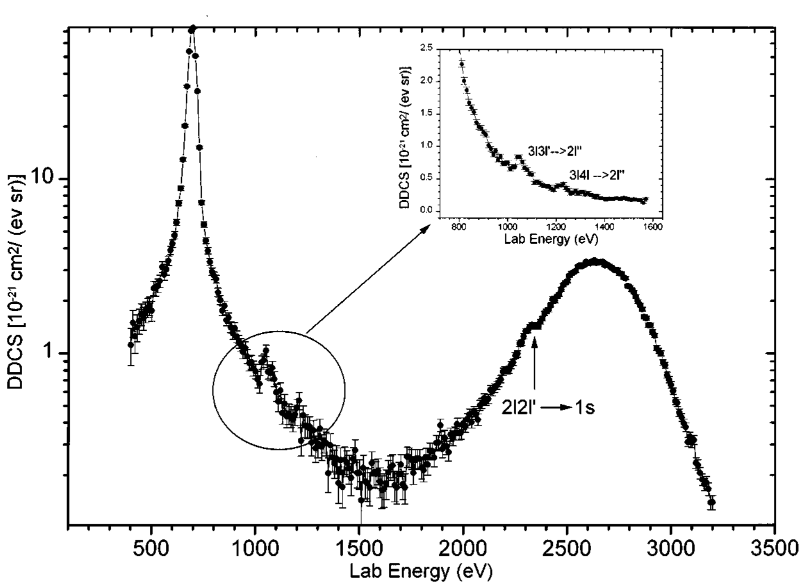

FIG. 2. Doubly differential cross sections for the electron production at 0° in the 20.25-MeV $O^{7+}(1s) + H_2$ collision as a function of laboratory electron energy. The inset shows the $3l3l'$ resonance region in low resolution.

between the direct and resonant inelastic scattering channels.

The ion-atom experiment was performed using 20.25-MeV O^{7+} projectiles incident on H_2. The ion beam was produced by the tandem Van de Graaff accelerator at the J. R. Macdonald Laboratory at Kansas State University. The energy of the electrons was analyzed at 0° using a tandem 45° parallel-plate electron spectrometer. The detailed description of the apparatus can be found elsewhere [20]. The electrons were recorded at 0° in the laboratory frame under single-collision conditions, which was found to be valid for target pressures below 50 mTorr in a 10-cm-long differentially pumped gas cell. The instrumental resolution of the spectrometer is 0.028. High resolution was achieved by decelerating the electrons between the two parallel plate analyzers to a constant energy. The absolute experimental resolution in the laboratory frame was 1.4 eV, which corresponds to a 0.4-eV resolution in the projectile frame. The ion beam was collimated by two sets of slits and two apertures, and was collected by a Faraday cup. The electron detection time at each electron energy was dictated by the number of projectiles collected by the Faraday cup. The typical time to obtain a high-resolution spectrum was about 10 min. for a 100-eV-wide laboratory electron-energy region at 100-nA beam current. Approximately 100 scans were performed on a 20-mT H_2 target.

The cross section due to the population of $3l3l'$ doubly excited states of O^{6+} can be seen in low resolution at laboratory energies of 1000–1100 eV in Fig. 2. The broad peak centered at about 2400 eV is the binary encounter peak that results from nonresonant elastic scattering in head-on collisions of the projectile with target electrons [21]. The arrow at 2400-eV laboratory energy indicates the position of the $2l2l'$ resonances that are due to the resonant elastic scattering of the quasifree target electrons on the projectile. These resonances have been investigated in great detail by several authors; see, for example, [22]. The dominant peak at 700 eV indicates electrons captured to the continuum (ECC) of the projectile.

The inset in Fig. 2 is an enlargement of the region of interest in low resolution and shows the $3ln'l'$ series. The high-resolution experiment, which will be described below, was performed on the $3l3l'$ resonances.

In summary, the following target ionization processes that contribute to the electron production are

$$O^{7+}(1s) + H_2$$
$$\downarrow$$

$O^{7+}(1s) + H_2{}^{+} + e^{-}$	ECC
$O^{7+}(1s) + H_2{}^{+} + e^{-}$	binary encounter
$O^{7+}(2l) + H_2{}^{+} + e^{-}$	direct inelastic scattering
$O^{6+}(3l3l') + H_2{}^{+}$	resonant excitation
$\downarrow$ $O^{7+}(2l) + H_2{}^{+} + e^{-}$	resonant inelastic scattering

The ECC and the direct inelastic excitation channel are the most important background contributions in the vicinity of the $3l3l'$ resonances. Since the electron yield from the ECC is orders of magnitude larger then the direct inelastic scattering, the experimental separation of these two electron production channels is not possible. Therefore we could obtain absolute cross-section data only for the resonant inelastic scattering contribution that is clearly distinguishable from the background processes.

The absolute efficiency of our spectrometer in low resolution was obtained by normalizing our binary encounter yield for $O^{8+} + H_2$ collisions to the elastic scattering model using the Rutherford scattering cross section [17]. By using a low-energy O^{8+} beam, for which the binary-encounter peak was near 1500-eV laboratory energy, it was confirmed that the efficiency of the spectrometer changes less than 5% over a wide range of electron energies. Hence the absolute spectrometer efficiency obtained from the binary encounter region for the 20.25-MeV O^{8+} beam could be used to get an experimental absolute single differential cross section (SDCS) value at the $3l3l'$ resonance energies. The SDCS was extracted by integrating over the energy region of the $3l3l'$ inelastic-scattering resonances after subtracting the significant background contribution that originates primarily from ECC electrons. The high-resolution spectra (see Fig. 3) was obtained by decelerating the electrons before the final stage of the energy analysis. This induces a significant decrease in the spectrometer efficiency. The SDCS in low resolution was used to normalize the SDCS in high resolution within the $3l3l'$ resonant inelastic-scattering region. Using this normalization technique, the absolute DDCS's for the resonant inelastic scattering was extracted from the high-resolution measurement. The experimental direct inelastic-scattering cross section was established by adding the theoretical direct inelastic-scattering cross section to the measured resonance cross section. This procedure does not affect the measured resonant DDCS's or the relative peak heights, which will be compared to the calculation.

The $3l3l'$ resonances associated with eight experimentally resolved peaks have been labeled in Fig. 3. This figure

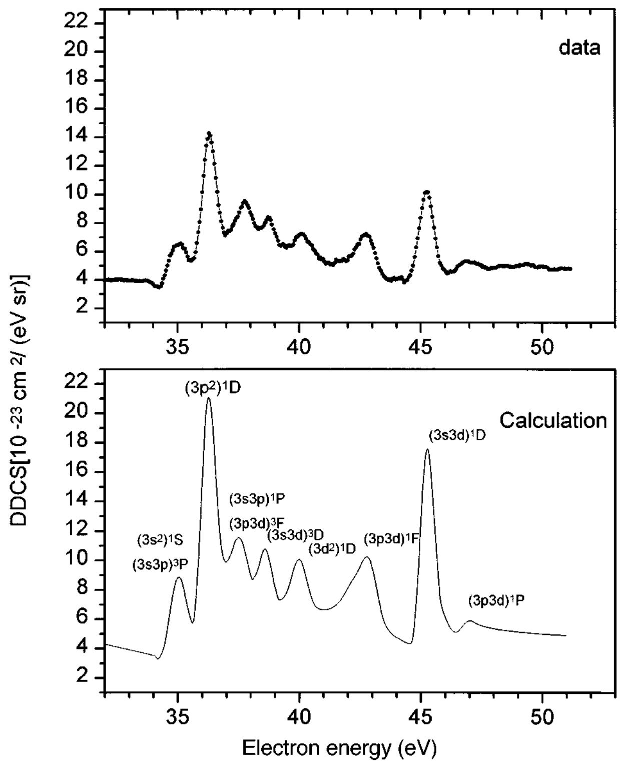

FIG. 3. Upper: Doubly differential cross sections as a function of outgoing electron energy in the projectile frame in the $3l3l'$ resonance region. Lower: Corresponding DDCS's calculated within the ISM convoluted with a 0.4-eV Gaussian.

contains a comparison between the experimental and calculated DDCS's for $O^{7+}+H_2$ as a function of the outgoing electron energy in the projectile frame at $\theta_{lab}=0°$. The theoretical cross sections (see Fig. 3), which are calculated within the inelastic electron-scattering model, have been convoluted with a 0.4-eV full width at half maximum Gaussian that is comparable to the experimental energy resolution in the projectile frame. As can be seen from this figure, the measured peak positions and the relative peak heights are predicted very well within the ISM. By integrating the experimental and calculated DDCS's with respect to the energy of the outgoing electron in the projectile frame, the theoretical resonant inelastic SDCS's were found to be 25% larger than the experimental resonant inelastic SDCS.

In conclusion, experimental absolute DDCS's for resonant inelastic scattering of $O^{7+}+H_2$ have been presented. The resonance features calculated within the ISM have been shown to be in excellent agreement with the experiment. The absolute theoretical resonant SDCS value differs from the experimental data by 25%. These results indicate that fast highly charged ion collisions with light gas targets can be used to obtain high-resolution, angle-resolved differential inelastic-electron-ion-scattering cross sections. Additional ion-atom experiments are needed to provide further tests of the ISM.

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