A.2. Electron-Ion Scattering—The Quasi-Free Electron Model

A.2.1. Elastic Scattering of Electrons from Ions--*Patrick Richard, Siegbert Hagmann and Chander Bhalla*

The study of the interaction of electrons with highly charged ions is of great interest due to their importance in high temperature ion-electron environments such as in plasma from fusion, discharges, and ion sources. For example electron-ion resonances can substantially alter the charge distribution and energy distributions in these systems. Measured and calculated differential electron scattering cross sections are important for the testing of models of inelastic energy loss processes, which lead to x-ray emission and charge transfer. Furthermore, knowledge of the resonances has long served as diagnostic information. It is important to understand which reactions are important and to include all the reactions that lead to the production of x-rays and ion charge change. The corona model developed to describe the solar surface temperature and density, and the opacity project developed to describe atomic processes in fusion plasma address these issues.

We proposed, in our last proposal, to measure and calculate the double differential scattering cross sections, DDCS, for the excitation of doubly-excited $2\ell n\ell'$ autoionizing resonances in ion-atom collisions. The calculations are based on the differential elastic scattering cross sections, DCS, of electrons on ions, which are transformed to the double differential scattering cross sections for the ion-atom collision by the Elastic Scattering Model, ESM. The ESM can also be used to convert the experimental DDCS to an electron-ion DCS.

The doubly excited autoionizing resonances are formed in the elastic scattering of the quasi-free electrons of the target from accelerated incident ions. The elastic scattering of electrons from the ions proceeds by two channels – the non-resonance channel and the resonance channel. The discrete resonances appear as sharp peaks on the continuous non-resonance elastic scattering channel (the binary encounter electron spectrum (BEE)). The amplitudes of the two processes interfere with each other to give rise to a Fano profile.

Many of the general features of electron emission from high velocity highly charged ion-atom collisions are understood in general terms [1]. There are three major identifiable structures in the electron emission spectra that can be associated with target and/or projectile ionization. The *first* is a low energy electron structure, accounting for most of the cross section, due to ionization in soft collisions resulting from the long-range interaction of the incident ions with the target bound electrons. The *second* is an intermediate energy, rather sharp structure called the cusp, due to electrons caught in the field of the moving ion and therefore moving with the projectile velocity, V_p. These electrons are the result of electron capture to the continuum if the electron comes from the target and electron loss to the continuum if the electron comes from the projectile. The *third* is a high-energy structure due to hard collisions between the ion and electrons of the target. The latter electrons are called binary encounter electrons, BEE, and have a large spread in velocity centered at approximately 2 $V_p \cos\Theta_L$, where Θ_L is the electron emission angle in the laboratory frame.

Non-resonance elastic scattering: The binary encounter electrons were the ones of interest in this study. It has been shown by several authors [2] that the double differential cross section, DDCS, for electron emission in ion-atom collisions can be transformed to the differential cross section, DCS, for electron scattering in a pure electron-ion collision when the DDCS is divided by the probability of having an electron of the proper energy and by performing the proper coordinate transformation. The model for making this connection is referred to as the Electron Scattering Model, ESM. The ESM equation relating these processes is given here (in atomic units):

$$\frac{d^2\sigma(E,\theta)}{d\Omega dE} = \frac{d\sigma(E,\theta)}{d\Omega}\frac{J(P_z)}{V_p + P_z} \tag{1}$$

where $J(P_z)$ is the Compton profile of the target electrons, and P_z is the momentum component of the target electron in the direction of the beam. Equation (1) can also be used to transform experimental ion-atom DDCS to electron-ion DCS and to compare them, therefore, directly with the theory for electron-ion collisions. This means that the ionization cross-section in the vicinity of the BEE for an ion-atom collision, forms a large database of electron-ion elastic scattering cross sections. The equations to perform the complete transformation from the laboratory frame of the ion-atom collision to the center-of-mass of the electron-ion collision are given here:

$$\cos\theta = \frac{\sqrt{t} - \sqrt{E_L}\cos\theta_L}{\sqrt{E}} \tag{2}$$

$$E_L = \left[\sqrt{t}\cos\theta_L + \sqrt{E - t\sin^2\theta_L}\right]^2 \tag{3}$$

$$\frac{d^2\sigma(E,\theta)}{d\Omega dE} = \sqrt{\frac{E}{E_L}}\frac{d^2\sigma(E_L,\theta_L)}{d\Omega_L dE_L} \qquad (4)$$

where t = $V_p^2/2$ is the cusp energy. The subscript L refers to the laboratory frame.

The BEE DDCS for the case of *bare ions* on light targets can be described by using the electron-bare ion Rutherford scattering formula for the DCS in equation (1) and then transforming it to the laboratory frame by equations (2-4). This is demonstrated in the upper part of Fig. 1, which depicts the electron emission spectra for 21.7 MeV $F^{9+} + H_2$ and $F^{8+} + H_2$ at zero degrees in the laboratory frame [see Publication #66]. The agreement between experiment and theory is excellent. To show how well this applies to obtaining electron-ion cross sections, the experimental DDCS data in the lab frame are transformed to DCS for electron-ion scattering in the center-of-mass frame (180° scattering in this case) using equations (1-4) and are then compared directly with theory as shown in the lower part of Fig. 1.

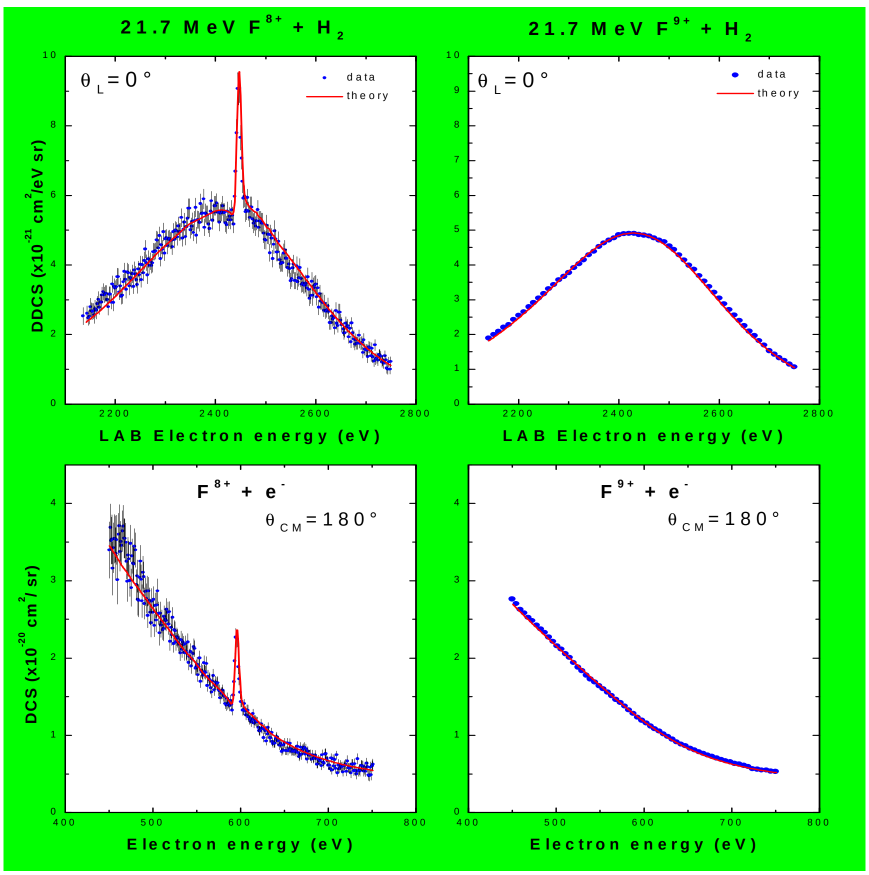

Figure 1. Electron spectra of F^{8+} and F^{9+} + He at 21.7 MeV in Lab and cm coordinates. The sharp resonance is the $(2p^2,{}^1D)$ state in F^{7+}. The upper curve is the Lab DDCS and the lower curve is the cm DCS.

The laboratory frame electron DDCS data for an ion-atom collision can be transformed to give the angular distribution of the elastic scattering of an electron for the ion with a well-defined energy in the center-of-mass. Figure 2 shows that transformation for the case of 30 MeV C^{6+} + H_2 electron emission data [see Publication #66, data from Publication #1]. This BEE database has been used to obtain 1400 eV electron-C^{6+} scattering cross sections. Both the Rutherford and the CDW-EIS calculations are shown for comparison purposes and exhibit excellent agreement with the transformed data in total support of the ESM.

The ESM model also has been used to interpret electron emission spectra for *non-bare ions* on light targets. Plotting the electron-ion DCS versus angle for fixed electron energy in the center-of-mass for the non-bare and bare ion cases best summarizes the results of these studies. Figure 3 shows the results for electron-F^{q+} scattering at 548.6 eV which is obtained from 19 MeV F^{q+} + H_2 data [3]. We see clearly in the figure the famous inverted q scaling [4] where

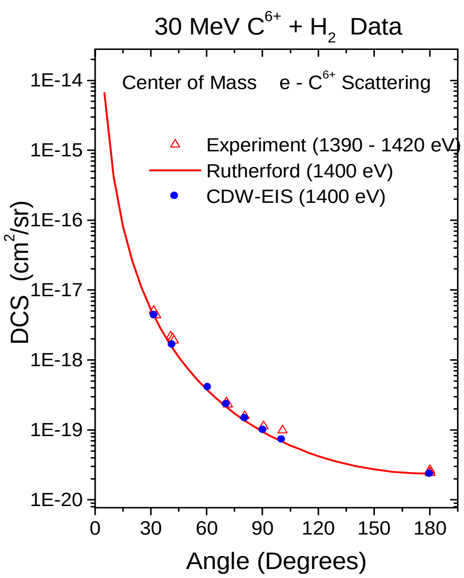

Figure 2. Angular DCS for electron-C^{6+} scattering deduced from 30 MeV C^{6+} + H_2 DDCS for 1400 eV electron energy.

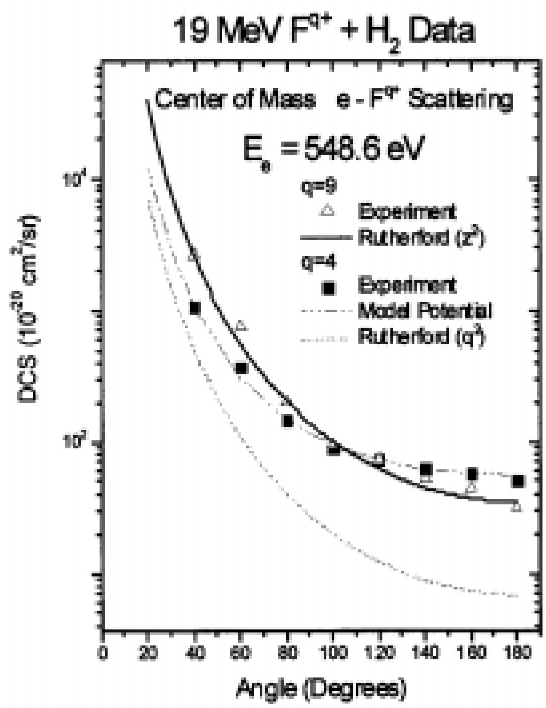

Figure 3. Electron angular distributions for 548.6 eV e^- + F^{9+} and e^- + F^{4+} collisions. Data from Liao *et al*. [3].

the F^{9+} to F^{4+} DCS ratio is much less than 1 at 180°. As the angular scattering in the center-of-mass decreases, we see that the ratio transforms to the normal q scaling. This is as expected since the small angle scattering corresponds to large impact parameter scattering. The theoretical calculations for electron-ion potential scattering for both charge states are also shown in the figure and agree very well with the experiment.

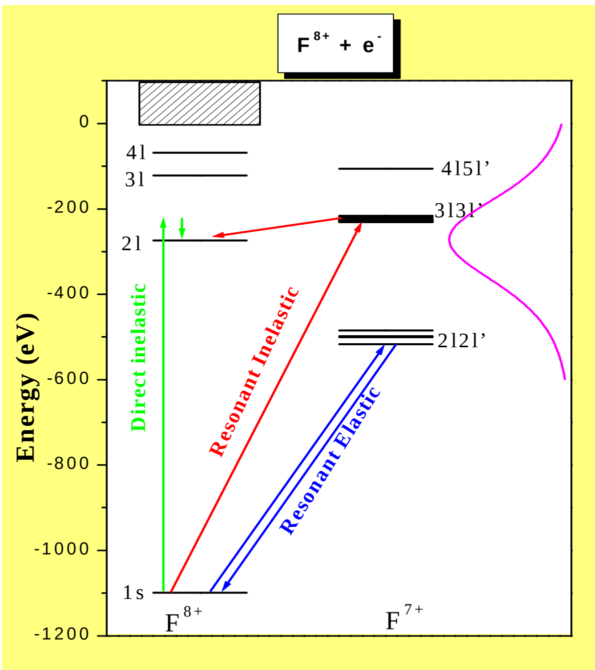

Figure 4. Energy level diagram for F^{8+} + e^-. Curve at the right shows a sample energy distribution of target electrons as seen by the moving projectile.

Elastic Scattering Resonances: Electron scattering from non-bare ions can lead to the formation of doubly excited resonance states. For example, electrons of approximately 594 eV bombarded on F^{8+}(1s) are at the resonant energy for forming the $F^{7+}(2p^2\ ^1D)$ doubly excited state [see Publications #66 and 69]. This doubly excited state can decay by x-ray emission, which leads to dielectronic recombination, DR, or by electron emission. Figure 4 shows the energy level diagram for the F^{8+} + electron system. A sample energy distribution of the incoming electrons (i.e., the distribution of target electrons as seen by the moving projectile) is shown on right of the figure. The electron emission from the doubly excited states is in the elastic scattering channel and is therefore coherent with the direct elastic scattering, which makes up the BEE peak. Figure 5 shows the electron emission data in the region of the $2p^2\ ^1D$ doubly excited state for C^{4+}, N^{5+}, O^{6+}, and F^{7+} [5,6]. The data are obtained by transforming the A^{q+} + H_2 electron emission data to the electron-A^{q+} data in the center-of-mass. The center-of-mass cross sections agree very well with theoretical calculations, which are shown by the solid line. The

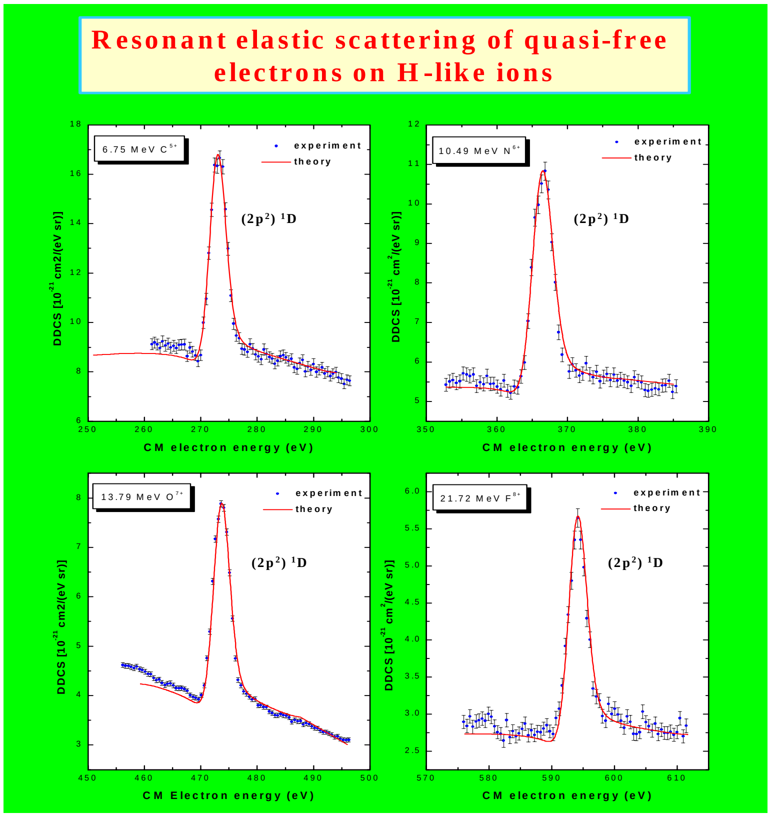

Figure 5. DDCS for C^{4+}, N^{5+}, O^{6+} and F^{7+} near the $(2p^2)^1D$ resonance.

non-symmetric resonance peak shape is due to the interference between the BEE and the resonance channels. This work establishes the base for further study and interpretation of DDCS from ion-atom collisions in terms of DCS for electron-ion resonance scattering processes. The latter has proven to be totally illusive in merged and crossed beam experiments. Even though DCS for electron scattering have been obtained for electron-ion collisions in a few cases [7-9], none have been successful in tracing out resonances in a merged/or crossed beam electron-ion scattering experiment. Total resonance cross sections have been measured for the related DR channel in ion storage rings with a very high precision center-of-mass energy by extracting the final charge-changed ion [10].

(G. Toth, S.R. Grabbe, P.A. Zavodszky, E.P. Benis, K. Zaharakis, M.M. Voultsidou, T.J.M. Zouros, C. Liao, C.L. Cocke, C.P. Bhalla, and P. Richard collaborated on this research project.)

Publications Related to Elastic Scattering of Electrons from Ions:

Publ. #17: "Elastic and Inelastic Scattering Models in Ion-Atom Collisions" by Grabbe, *et al.*

Publ. #50: "A New Hemispherical Analyser with 2-D PSD and Focusing Lens for Use in 0° Electron Spectroscopy," by Benis, *et al*.

Publ. #64: "Differential Electron –Cu^{5+} Elastic Scattering Cross Sections Extracted from Electron Emission in Ion-Atom Collisions," by Liao, *et al*.

Publ. #66: "Quasi-free Electron-Ion Scattering in Ion-Atom Collisions," by Richard, *et al*.

Publ. #68: "Resonant Two-Electron Processes in Ion-Atom Collisions," by Zavodszky, *et al*.

Publ. #69: "High-Resolution RTE Measurements at 0° Using a Hemispherical Analyzer With Lens and a 2-D PSD," by Benis, *et al*.

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