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Production of Autoionizing Rydberg States by Transfer Excitation in High Energy Ion Atom Collisions

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Abstract

The method of zero-degree Auger spectroscopy was used to study the production of autoionizing Rydberg states in collisions of carbon and oxygen projectiles incident at several MeV on He gas and carbon foils. The autoionization electrons were measured with high resolution so that the quantum defect corresponding to the angular momenta of the Rydberg electrons could be observed. The main purpose of the present experiment is to gain information about the n and ℓ distribution of the Rydberg electron captured in the collision. The well-known n^{-3} law is confirmed. For the He gas target it is found that the angular momenta p and d are predominantly produced. For the foil target the higher angular momenta are clearly enhanced.

I. Introduction

In energetic ion-atom collisions the collision partners can be excited above the ionization threshold giving rise to the emission of Auger electrons. The spectroscopy of ion-induced Auger electrons has received particular attention, as it provides information about the collision process as well as the structure of the excited atom. Since the properties of highly ionized atoms are of great current interest, considerable attention has been devoted to the study of the projectile ions. The incident particle can be prepared in a specific charge state and its excitation can be studied in single collisions with gaseous target atoms.

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When a vacancy is collisionally created in a low lying subshell of the ion and it is filled by an electron from a subshell with the same principal quantum number, the energy of the ejected electron is rather low. In fact, usually, these Coster-Kronig transitions are energetically forbidden in highly ionized atoms. They become possible, however, when loosely bound Rydberg electrons are involved. Hence, the study of the electrons from the Coster-Kronig transitions provides information about the Rydberg states occupied in ion-atom collisions.

Because of kinematic effects, the low-energy electrons can only be seen in a small cone of forward angles. Thus, it is useful to measure the autoionization electrons at 0° observation angle with respect to the incident beam direction. In this case, the autoionization electrons are seen in the vicinity of the electron loss to continuum[1] (ELC) or the electron capture to continuum (ECC) peak.[2] These cusp shaped peaks are centered at an electron energy which corresponds to the velocity equal to the projectile velocity.[3] The low-energy autoionization electrons are superimposed on the wings of the cusp peak as first observed by Lucas and Harrison.[1] Similar measurements[4-7] of the projectile autoionization electrons have revealed a number of peaks which have been attributed to a series of Rydberg states. Most studies[4-7] have been devoted to the configuration $1s^2 2pn\ell$ giving rise to autoionization electrons whose energy increases with increasing quantum number n.

Most previous studies[4-6] of the projectile autoionization electrons have been made with intermediate resolution with which it was possible to resolve line groups associated with the n-quantum number of the Rydberg electron. The resolution, however, was not sufficient to separate structures in a given line group. There are no major problems with high resolution measurements of the autoionization electrons, since kinematic line broadening effects cancel in first order[8] when the electrons are observed at 0°. Indeed, Schneider et al.[7] recently have observed spectral structures which could be attributed to the ℓ-quantum number of the Rydberg electron. This opened the possibility to gain information about the angular-momentum of the Rydberg states occupied in the collision.

In this work, high-resolution measurements were made of autoionizing Rydberg states to study the n and ℓ distributions produced in collisions of carbon and oxygen with He at projectile energies of several MeV. Emphasis here is on the investigation of capture processes involved in the production of the autoionizing states. Furthermore, the results obtained with the He gas target are compared with data measured with a foil target.

II. Experimental method.

The experiments were performed at the Oak Ridge National Laboratory EN Tandem facility using the zero-degree Auger spectroscopy apparatus[9] temporarily transported from Hahn-Meitner Institut Berlin. Most experiments were made with C^{2+} and C^{3+} of several MeV incident on He and on carbon foils. Furthermore, 10-MeV O^{3+} and O^{4+} projectiles were used. The experimental set-up is shown in Fig. 1. Electrons produced in the target gas cell were measured at the observation angle of 0° with respect to the beam direction by a tandem electron spectrometer. It consists of two consecutive 90° parallel-plate electrostatic

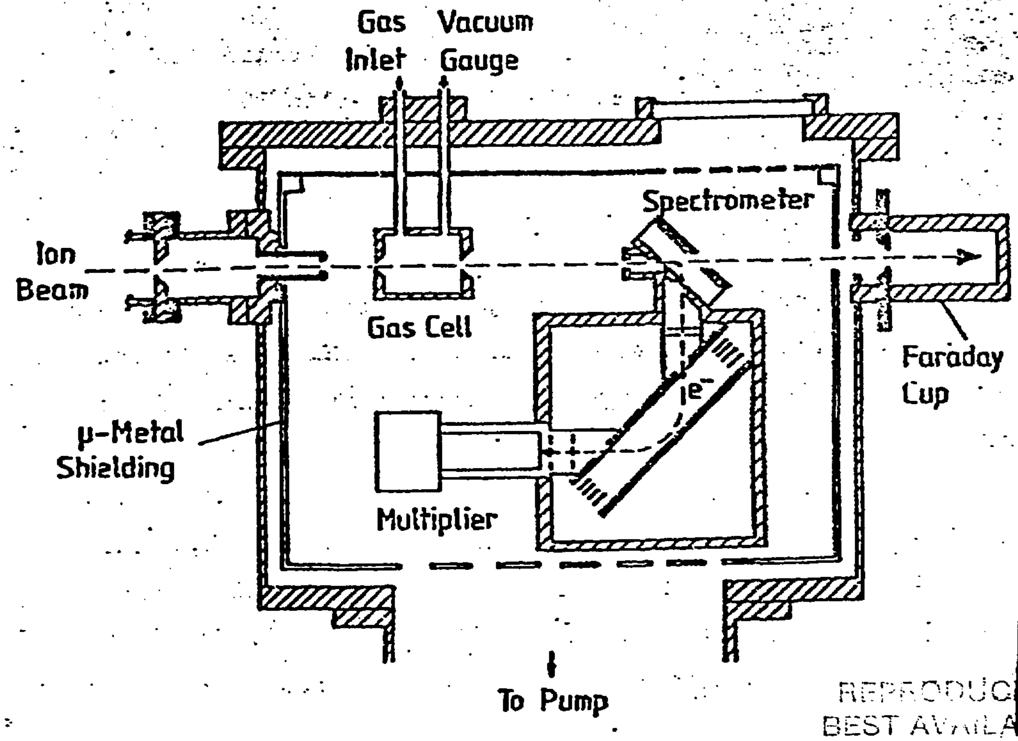

Fig. 1. Experimental set-up used for the electron measurements at zero-degree observation angle.

energy analyzers. The entrance analyzer is used as a deflector to steer the electrons out of the ion beam as well as to suppress spurious stray electrons. The exit analyzer determine the electron energy with high resolution. To improve the resolution, the electrons were decelerated in a lens system in front of the exit analyzer. Thus, a typical energy resolution of $\Delta E/E=10^{-3}$ was achieved. The electron acceptance (half) angle was 1° which is expected to be reduced by the deceleration of the electrons.

Care was taken to maintain single-collision conditions. The target cell has a length of 5 cm. The He gas pressure in the target cell and the scattering chamber was about 10^{-2} and 10^{-4} Torr, respectively. In representative cases measurements were made for different target gas pressures to ensure a linear pressure dependence of the electron yield. The beam current was typically 10 nA and 100 nA in the foil and gas target experiments, respectively. Usually, rates of several thousands counts per seconds were achieved so that a typical electron spectrum could be acquired at less than 30 min.

III. Results and Discussion.

Figs. 2 and 3 show examples for electron spectra which are representative of the collision systems studied. Fig. 2 clearly indicates cusp shaped electron loss peaks underlying the autoioniztion lines. However, surprisingly, Fig. 3 shows that the electron loss peak for O^{3+}+He has a flat top which has been found to be reproducible. The interpretation of this mesa shape of the electron loss peak lies outside the scope of the present article and it is left to a forthcoming communication.[10]

On the wings of the electron loss peak, various structures are seen originating from autoionizing Rydberg states. In the case of the 10-MeV O^{3+}+He system the incident configuration $1s^22s^22p$ is converted by excitation of a 2s electron into the configuration $1s^22s2pn\ell$ which form a large number of states. The coupling of the 2s2p core to the parent terms ^1P and ^3P produces two different series limits. Moreover, coupling of the core with the Rydberg electron yields numerous doublet and quartet terms which are partially resolved. Hence, in Fig. 3, the spectrum is of great complexity and it shall not further discussed here. Rather, the attention is focussed on the simpler systems shown in

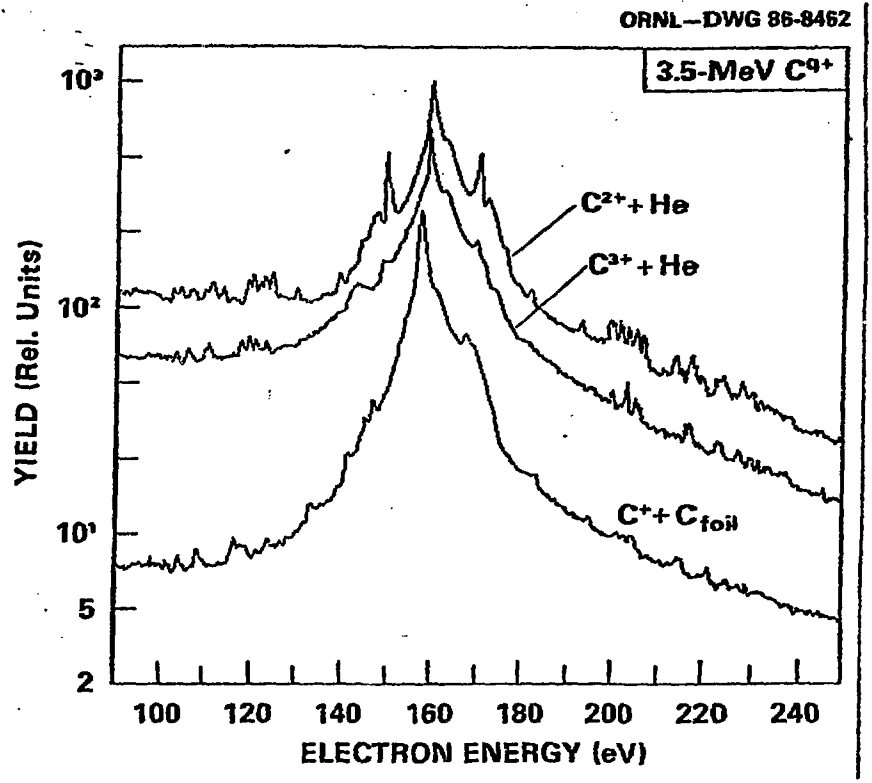

Fig 2. Electron spectra produced in 3.5-MeV C^{2+}+He, C^{3+}+ He and C^{+}+C (foil) collisions. The electron energy refers to the laboratory rest frame. Small energy shifts are visible due to the projectile energy loss in the foil and the stripper gas in the accelerator.

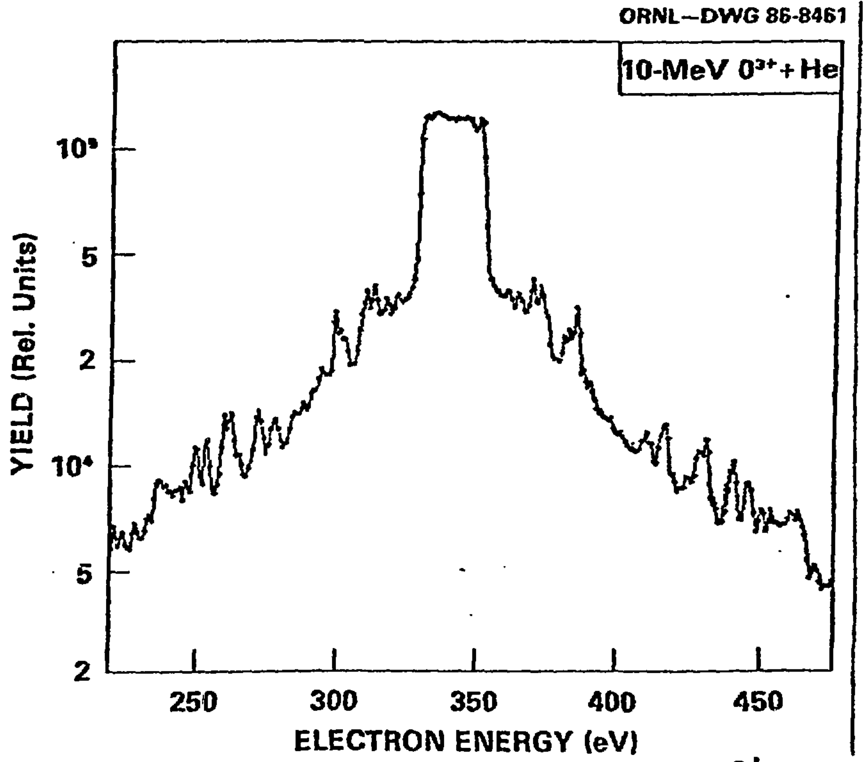

Fig. 3. Electron spectrum produced in 10-MeV O^{3+} + He collisions. The electron energy refers to the laboratory

Fig. 2. As in previous studies[4-7] the spectra here exhibit line groups primarly due to the configurations $1s^22pn\ell$.

The autoionization lines are strongly influenced by kinematic effects.[8] For instance, the structures on the low-enery side are produced as the reflected image of those on the high-energy side. This is caused by kinematic line doubling effects, i.e., the low- and high-energy lines are due to the ejection of the autoionization electrons at 180° and 0° in the projectile rest frame, respectively.

The low energy ε_L and the high energy ε_H of corresponding lines in the laboratory rest frame transform into the energy ε' of the projectile rest frame by

$$\varepsilon' = (\varepsilon_{L,H}^{1/2} - t_p^{1/2})^2$$

where t_p is the projectile energy divided by the projectile-electron mass ratio. Moreover, the differential cross section in the laboratory frame transforms into the projectile rest frame by the relation

$$\frac{d\sigma}{d\Omega d\varepsilon} = (\varepsilon/\varepsilon')^{1/2} \frac{d\sigma}{d\Omega' d\varepsilon'}$$

where ε equals to ε_L or ε_H.

After the transformation into the projectile rest frame, the low- and high-energy spectra are generally found to be identical within the statistical errors. However, in specific cases (e.g. C^{3+}+ He in Fig. 2) the corresponding line structures at low and high energies do <u>not</u> agree indicating that the ejection of the autoionization electrons is not symmetric about 90° in the projectile frame. Future work is suggested to study this phenomenon which is possibly produced by post-collision Stark effects.[12]

Fig. 4 shows the electron spectrum for the 3.5-MeV C^{3+}+ He system obtained after the transformation into the projectile rest frame and the subtraction of the continuous electron background. In collisions of C^{3+} on He, the incident configuration $1s^22s$ is converted by a transfer-excitation process to the configuration $1s^22pn\ell$. If, for a moment, the term splitting produced by the coupling of the 2p and $n\ell$ electron is disregarded, it follows that the energy of the ejected autoionization electron is given by[4]

$$\varepsilon_{n\ell} = \Delta E_{2s2p} - \frac{Q^2}{(n-\mu_\ell)^2}\,\mathrm{Ry}$$

where ΔE_{2s2p} is the energy difference between the 2s and 2p orbitals, Q is the effective charge of the atomic core seen by the Rydberg electron, and μ_ℓ is the quantum defect associated with the angular momentum ℓ. In Fig. 4, the spectrum clearly exhibits the peak groups associated with the n and ℓ quantum numbers of the Rydberg electron.

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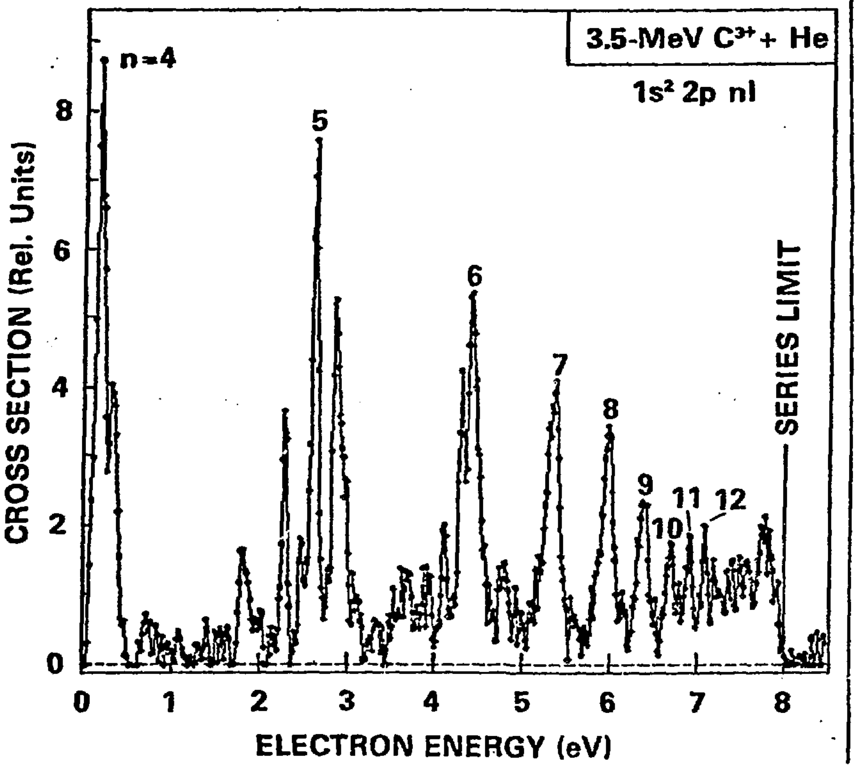

Fig. 4. Electron spectrum produced in 3.5-MeV C^{3+}+ He collisions (Fig. 2). The electron energy refers to the projectile rest frame. The continuous electron background is subtracted.

It is seen that the Coster-Kronig transitions become energetically allowed when $n \geq 4$. The case n = 4 is particularly interesting, since some of the states produced in that group fall below the zero energy threshold and other states are produced just above the threshold.[12] For instance, we observe a line at 0.18 eV which may be attributed to the term $1s^22p4d\ ^3D$. For 5-MeV C^{3+}+He this line has found to have a width of 20 meV in the projectile frame demonstrating the rather high resolution obtained by the present method of zero-degree Auger spectroscopy. Before we analyze the data in more detail, we consider the intensities of the integrated peak groups to verify wether the Rydberg states are populated according to the well-known n^{-3} law. Fig. 5 shows results for the collision system 5-MeV C^{3+} + He. The experimental data are compared with calculated values proportional to n^{-3}. It is seen that the data points are indeed well fitted by the (normalized) n^{-3} curve.

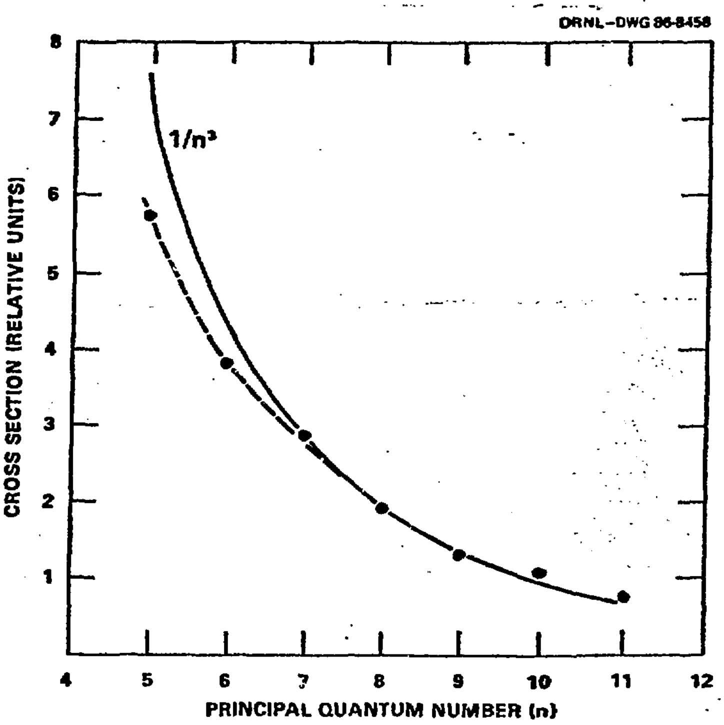

Fig. 5. Cross Section for the production of autoinizing configuration $1s^22pn\ell$ in 5-MeV O^{3+} + He collisions. The experimental data are compared with calculated values proportional to n^{-3}. The calculated curve is normalized to the experimental data for n = 8.

To analyze the structures in the peak groups, the experimental data are compared with theoretical transition energies provided by Griffin et al.[12] and Theodosiou.[13] Fig. 6 shows results for the peak group associated with the pricipal quantum number n = 5. It is seen that the term splitting produced by the coupling of the Rydberg electron with the 2p electron is not negligible as assumed previously. In fact the term splitting is of the same order of magnitude as the quantum defect. It should be added that the spin-orbit splitting of the multiplets is small for the carbon ion studied here.

In Fig. 6 the spectrum exhibits three prominent peaks which can be attributed to the angular momenta of the Rydberg electron. The first peak is due to the single term $1s^22p5s\ ^3P$ which represents the s state of the Rydberg electron. Similarly, the second peak is composed of lines attributed to the p state of the Rydberg electron. The third peak, however, contains lines due to terms formed by p, d, and, some f states. Estimates show that the contributions from the p state amounts to about 30% of the total intensity.

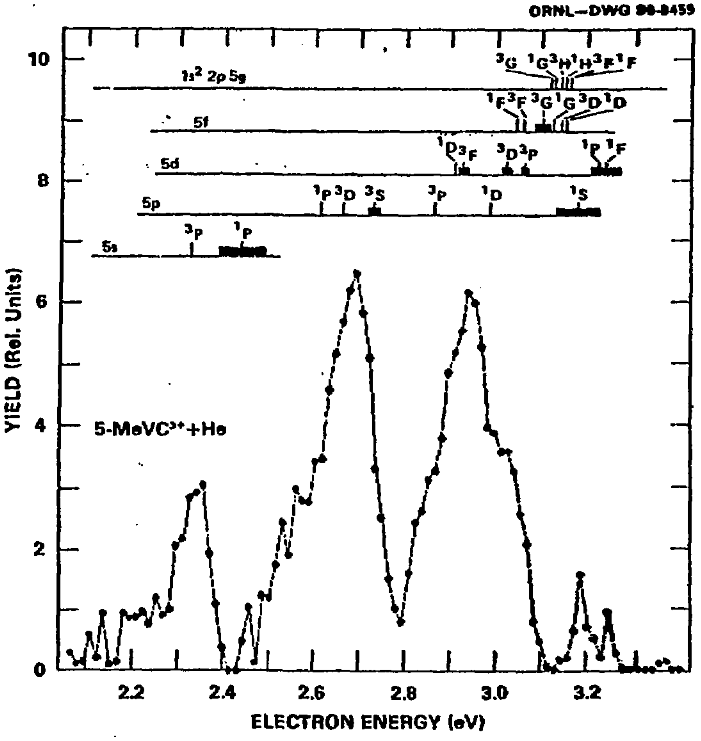

Fig. 6. Spectrum of the peak group associated with the configuration $1s^22p5\ell$ produced in 5-MeV C^{3+} He collisions. The electron energy refers to the projectile rest frame. The term energies and widths given above the spectrum are based on calculations by Griffin et al.[12] and Theodosiou.[13]

Then, from the line intensities it follows that in collisions of 5-MeV C^{3+} on He the angular momenta s, p, and d are produced with the approximate probability of 0.2, 0.5, and 0.3, respectively. For lower projectile energies the contribution from the s state is found to be enhanced. These results are obtained with the assumption that the ejection of the autoionization electrons is isotropic, i.e. the magnetic quantum numbers M of a given term are equally populated. It is noted that the present method of zero-degree spectroscopy is sensitive only to the substate M = 0.

Finally, a preliminary analysis was made for the data obtained with carbon foils. The spectra clearly show that for n = 5 the high angular momenta such as f and g are preferentially produced in the foil target. This result is in qualitative agreement with the predictions of the random walk model by Burgdörfer and Bottcher.[15] Further work is needed to obtain quantitative results for the angular momenta of the Rydberg electron from the complex autoionization spectra produced in the carbon foils.

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References

1) M. W. Lucas and K. G. Harrison, J. Phys. B 5 (1972) L20

2) D. Burch, H. Wieman, and B. Ingalls, Phys. Rev. Lett. 30 (1973) 823

3) M. Breinig, S. B. Elston , S. Huldt, L. Liljeby, C. R. Vane, S. D. Berry, G. A. Glass, M. M. Schauer, I. A. Sellin, G. D. Alton, S. Datz, S. Overbring, R. Laubert, and J. M. Suter, Phys. Rev. A 25 (1982) 3015

4) M. Suter, C. R. Vane, S. B. Elston, G. D. Alton, P. M. Griffin, R. S. Thoe, L. Williams, and I. A. Sellin, Z. Phys. 289 (1979) 433

5) L. H. Anderson, M. Frost, P. Hvelplund, H. Knudsen, and S. Datz, Phys. Rev. Lett. 52 (1984) 513 and L. H. Anderson, M. Frost, P. Hvelplund and H. Knudsen, J. Phys. B 17 (1984) 4701

6) A. Itoh and N. Stolterfoht, Nucl. Instr. Meth. B10/11 (1985) 97

7) Th. Schneider, D. Schneider, W. Zeitz, G. Schiwietz, H. Platten, U. Stettner, and N. Stolterfoht, 6. Arbeitstagung für energiereiche atomare Stösse (Obersdorf, 1985) unpublished

8) N. Stolterfoht, A. Itoh, D. Schneider, Th. Schneider, G. Schiwietz, H. Platten, G. Nolte, R. Glodde, U. Stettner, W. Zeitz, and T. J. Zouros, International Conference on X-Ray and Inner-Shell Processes in Atoms, Molecules, and Solids, edited by A. Meisel (Leipzig,1984) p. 193

9) A. Itoh, D. Schneider, T. J. Zouros, G. Nolte, G. Schiwietz, W. Zeitz, and N. Stolterfoht, Phys. Rev. 31 (1985) 684

10) The mesa shape of the electron loss peak is associated with autoionization lines measured in high resolution

11) N. Stolterfoht, D. Brandt, and M. Prost, Phys. Rev. Lett. 43 (1979) 1654

12) D. C. Griffin, M. S. Pindzola, and C. Bottcher, Phys. Rev. A 31 (1985) 568 and D. C. Griffin, private communication

13) T. E. Theodosiou using the computer code by Grant et al.,[14] private communication (1985)

14) I. P. Grant, B. J. McKenzie, P. H. Norrington, D. F. Mayers, and N. C. Pypar, Comm. Phys. Comm. 81 (1980) 207

15) J. Burgdörfer and C. Bottcher, to be published