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Absolute Doubly Differential Cross Sections for Production of Electrons in Ne^+-Ne and Ar^+-Ar Collisions

R. K. Cacak and T. Jorgensen, Jr.
Department of Physics, University of Nebraska, Lincoln, Nebraska 68508
(Received 17 April 1970)

Absolute differential cross sections for the production of electrons by collisions of neon ions with a neon-gas target and argon ions with an argon-gas target were measured. The cross sections were doubly differential in angle and energy of the ejected electrons. The energy range of the primary ions was 50 to 300 keV. Electrons that were produced by the ion-atom collisions were analyzed in angle and energy, counted, and, from a knowledge of the other parameters of the apparatus, an absolute cross section was determined. The experimental results show some structure in the electron-energy spectra superimposed on a continuous background. This is consistent with the predictions of the Fano-Lichten electron-promotion model. Calculations based on the results of the Russek statistical model are compared with experiment.

I. INTRODUCTION

Ionizing collisions of symmetric heavy ion-atom collisions of the type

$$Ne^+ + Ne \to Ne^{+m} + Ne^{+n} + (m+n-1)e^- ,$$

$$Ar^+ + Ar \to Ar^{+m} + Ar^{+n} + (m+n-1)e^-$$

are, in general, too complex to treat in a conventional quantum-mechanical manner, and other theoretical models have been proposed to explain some of the features of these collisions. Russek and his co-workers[1] have developed a statistical theory that successfully predicts the probability of an ion appearing in a certain charge state after the collision as a function of other collisional parameters. Recently, Russek and Meli[2] have calculated the energy distribution of the electrons produced as a function of the energy transfer in a collision. These results were converted to cross sections by Bierman *et al.*[3] using the energy-transfer distributions of Everhart and Kessel[4] and empirical data relating the distance of closest approach to the energy transfer.[5] Bierman's calculations were compared to the energy spectrum of electrons from argon obtained earlier at this laboratory.[6] The agreement was fair, but the experimental data were incomplete.

Structure in the collisional energy-loss spectra stimulated Fano and Lichten to propose an electron "promotion" model based on the theory of molecular orbitals.[7] A consequence of their model was the prediction of discrete peaks in the spectra due to transitions from autoionizing and Auger levels in the collision partners. The cross sections for exciting the Auger levels in neon and argon will be discussed in the following paper.[8]

The experiment described here provides the electron-production cross sections, differential in energy and angle of the ejected electrons, and uses incident-ion energy as an additional parameter. The processes studied were the symmetric collisions: neon ions incident upon a neon-gas target and argon ions upon an argon-gas target. The ion energy ranged from 50 to 300 keV in steps of 50 keV. The ion beam was magnetically analyzed and had a relatively small spread in energy. The range of angles of electron ejection was from 10° to 160° with respect to the ion beam, and the electron energy range was from about 1.5 eV to 1 keV. The cross sections were measured in an absolute sense and are independent of other experimental results.

The purpose of this experiment was not to analyze or label any of the structure in the electron-energy spectrum. The resolution of the apparatus was made purposely low to increase the counting rate, and the emphasis was on measuring the absolute value of the continuous portion of the spectrum as well as the absolute value of various structures.

II. APPARATUS

A collimated beam of energetic ions, produced by a Cockcroft-Walton accelerator, was allowed to enter the collision chamber containing the target gas. The chamber was basically that described by Rudd *et al.*[9] with some improvements. Only a brief description will be given here since a complete description is available elsewhere.[10]

Electrons were produced by both an ionization of the target-gas atoms and a stripping of the incident ions. The resulting electrons were energy analyzed with a 127° electrostatic analyzer and individually counted with an electron multiplier. The ion current was time integrated, and after a certain accumlation of charge, the electron-counting scaler was automatically shut off. The pressure of the target gas, usually $3-5\times10^{-4}$ Torr, was measured with a "Baratron" capacitance manometer.

The efficiency of the electron-detection system was determined by comparing the electron-counting rate to the electron current. To facilitate the handling of small currents, a system of different-sized moveable apertures (similar to the apparatus used by Allen[11]) was inserted into the electron beam. The ratios of the sizes of these apertures were determined by measuring the ratios of currents passed by them. The current was supplied by an electron gun which was greatly defocused to insure a uniform flux of electrons. Knowing the ratio of the size of the apertures, the absolute current, and the counting rate, the counting efficiency of the electron multiplier and associated apparatus was determined to be 0.81 ± 0.06.

Both steady and ac magnetic fields near the paths of the electrons were nulled using a system of three pairs of mutually perpendicular Helmholtz coils. The coils were about 120 cm diam, and the chamber was placed near the center of them. To count low-energy electrons reproducibly, the magnetic field in the region of the electron trajectory was made as small as possible. With the present system of coils, fields as small as 6 mG were achieved. Cross sections for electrons with energies above 12 eV could be reproduced to within ± 5% from day to day. Below this energy, the data could not be reproduced to better than ± 25%.

By knowing the geometry of the chamber, the density of the target gas, the number of ions and electrons, and the efficiency of the system, the absolute doubly differential cross section $\sigma(E_0, \theta)$ was determined.[10] Here E_0 is the electron energy, and θ is the angle at which the electron was ejected. Ionization cross sections differential in one variable only are defined

$$\sigma(\theta)=\int \sigma(E_0,\theta)\, dE_0\ , \tag{1}$$

$$\sigma(E_0)=\int \sigma(E_0,\theta)\sin\theta d\theta\, d\phi\ . \tag{2}$$

The total ionization cross section σ_{tot} is defined by an integration over the remaining variable

$$\sigma_{tot}=\int \sigma(E_0)\, dE_0=\int \sigma(\theta)\sin\theta\, d\theta\, d\phi\ . \tag{3}$$

The relative uncertainty of the cross sections is the square root of the sum of the squares of the relative uncertainties of each of the measured parameters determing $\sigma(E_0, \theta)$. If the experimental value of a parameter is X, and if the true value lies between $X-\delta X$ and $X+\delta X$ with nearly complete certainty, then $\delta X/X$ is defined as the relative uncertainty of that parameter. The relative uncertainty of the cross sections $\sigma(E_0, \theta)$ above 12 eV determined in this manner is ± 14%. The cross section $\sigma(E_0, \theta)$ at lower electron energies and the resulting calculations of $\sigma(\theta)$ and σ_{tot} that involve an integration over the large number of low-energy electrons have a larger uncertainty. Typical relative uncertainties for these quantities are ± 35%.

III. EXPERIMENTAL RESULTS

The doubly differential cross section for electron production at the various angles have similarly shaped curves although, in general, the absolute magnitude is different. Only a sampling of the total results, which are available elsewhere,[10] is illustrated in Figs. 1 and 2. Each curve represents the cross section for a different ion energy. The shape of these cross sections at $\theta = 90°$ is representative of other angles.

For both the neon and argon systems, there is a preponderance of low-energy electrons. The cross section falls off quickly with higher electron energies. The neon curves closely approximate an exponential decrease.

It was previously noted[6] that the argon spectrum consists of two types of spectra. One is a "background" or continuous distribution of electrons similar to what is observed in neon. The other type consists of two groups of structure superimposed upon the continuum. The most prominent is a series of peaks caused by L-shell Auger transitions that occurs about 150–230 eV. These peaks are unresolved and appear as one large peak in the present data. The other structure is a small shoulder on the continuum near 12–14 eV. The latter peak is attributed to autoionizing transitions. Both of these structures were predicted by Fano and Lichten.[7] The analogous K-shell Auger peak in neon emerges out of the statistical fluctuations at about 730 eV and is not shown here.

Because of the low resolution of the analyzer, the Auger peaks in both gases and the autoionizing peak (about 12 eV) in argon are the only peaks observed. Other experimenters[12] have resolved these peaks into several lines and have also observed other lines that were not seen here.

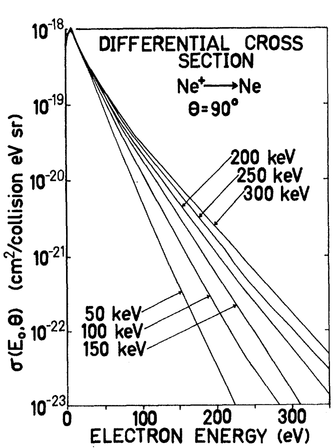

FIG. 1. Doubly differential electron-production cross section $\sigma(E_0, \theta)$ at $\theta = 90°$ for several different ion energies plotted as a function of electron energy. Neon ions and neon target gas were used. The shape of these curves are typical of other angles.

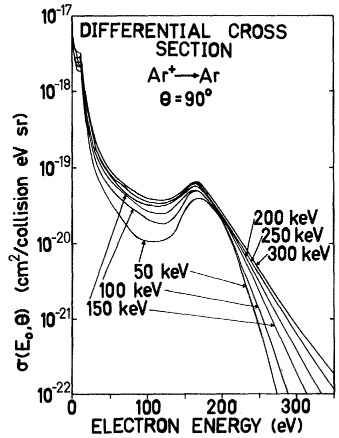

FIG. 2. Doubly differential electron-production cross section $\sigma(E_0, \theta)$ at $\theta = 90°$ for several different ion energies plotted as a function of electron energy. Argon ions and argon target gas were used. The shape of these curves are typical of other angles.

Over the range of ion energies studied, the continuum cross section increases with increasing ion energy. An exception to this occurs at the top of the Auger peak in argon. The peak height remains nearly constant over the range of ion energies studied, and is also nearly isotropic in angle.

The angular distribution of the cross section at two particular electron energies is shown in Fig. 3. The upper curves show the dependence on angle for an electron energy that lies in the continuum

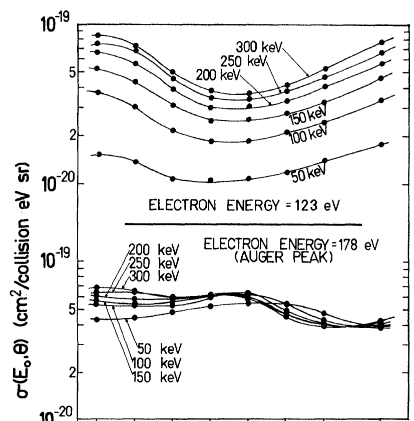

FIG. 3. Doubly differential electron-production cross section plotted as a function of angle for two different electron energies in argon. The top curves are characteristic of the angular- and ion-energy dependence of cross sections in the continuum. The bottom curves are characteristic of the dependence of the cross section near the Auger peak.

of argon. The shape of this cross section is typical of the continuum distributions in both argon and neon. More electrons are ejected in the direction of the ion beam, i.e., at small angles. A smaller maxima at large angles is seen in addition to the small angle increase. The increase of the cross sections with increasing ion energy is also clearly indicated by Fig. 3.

The lower set of curves in Fig. 3 represents the value of the cross sections near the Auger peak of argon. The electrons with this energy are ejected more isotropically and are more independent of ion energy than the continuum electrons. The Auger electrons from neon (not shown) are also somewhat isotropic but are dependent on ion energy.

The difference in shape of these two cross sections indicates something about the electron's origin. If the continuum electrons are due to a series of many closely-spaced discrete autoionizing or Auger states in the atom, then the angular distribution of continuum electrons would be expected to be nearly as isotropic as the Auger electrons. The data refute this explanation of the origin of continuum electrons. At energies higher than the Auger energy, electrons would have to be ejected via transitions from states deeper to the atoms. However, even the higher-energy continuum electrons have angular distributions characteristic of the continuum electrons in Fig. 3.

The cross section, differential in angle only [as defined by Eq. (1)], has an angular dependence similar to the continuum electrons except that the forward peak is more pronounced. The cross sections $\sigma(\theta)$ for neon and argon are shown as Figs. 4 and 5, respectively. The argon cross sections

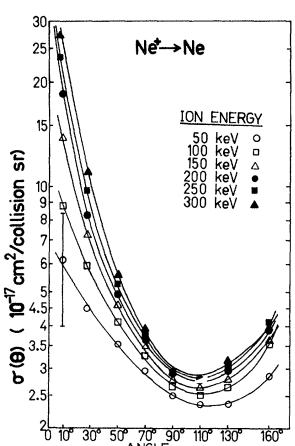

FIG. 4. Electron-production cross sections differential in angle after integrating over all electron energies according to Eq. (1). The ion and target are neon.

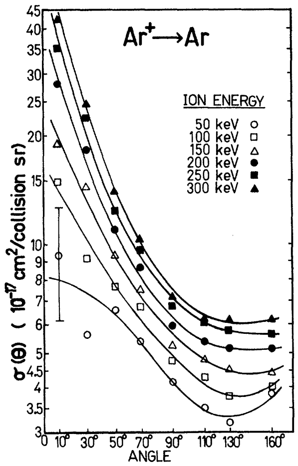

FIG. 5. Electron-production cross sections differential in angle after integrating over all electron energies according to Eq. (1). The ion and target are argon.

are, in general, higher than those of neon for the same ion energy. The neon curves indicate a distinct increase at large angles, whereas the argon cross sections increase only slightly.

The cross section $\sigma(E_0)$ after integrating $\sigma(E_0, \theta)$ over the entire 4π solid angle, as indicated by Eq. (2), is shown in Figs. 6 and 7 as a function of electron energy. Many of the same features of the doubly differential cross sections are also apparent here. Again, the cross section at the Auger peak

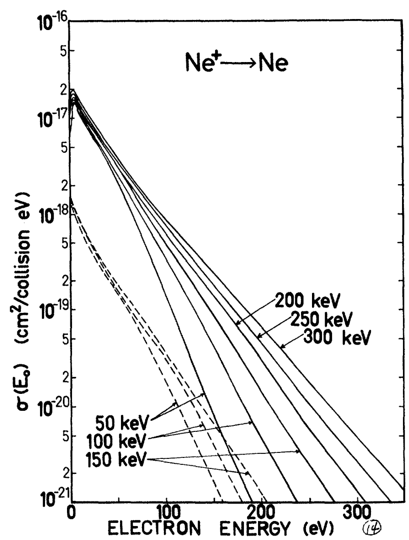

FIG. 6. Differential electron-production cross sections of neon for different ion energies (solid curves) after integrating over all angles. The dotted curves are the results of the statistical calculations made according to the prescription of Refs. 2 and 3.

of argon is constant over the range of ion energies.

The dotted lines of Figs. 6 and 7 are the results of the statistical cross-section calculations made by us for lower ion energies according to the prescription of Bierman *et al.*[3] and Russek *et al.*[2] The present calculation has used the energy-loss data of Kessel *et al.*[13] rather than the experimental results of Morgan *et al.*[5] that were used in Bierman's calculation. The cross sections predicted by this theory are mostly lower than experimental results. The calculations do show qualitative agreement, however. They predict a large number of low-energy electrons and a cross section that decreases rapidly with increasing electron energy. Both the experimental and the calculated cross sections diverge at larger electron energies for different ion energies. The exponential dependence of the neon continuum is also shown by the calculations.

The statistical theory does not predict any structure due to inner-shell excitations. The large Auger peak in argon is essentially ignored by the theory. The results of the calculation shown in Fig. 7 are low by at least a factor of 10 for low electron energies and intersect the experimental curves at intermediate energies. At higher energies, the calculations seem to rise above the experimental points. In the case of argon, the theory also shows some of the qualitative features of the experiment, but the absolute values are in general quite different.

The absolute total cross section for production

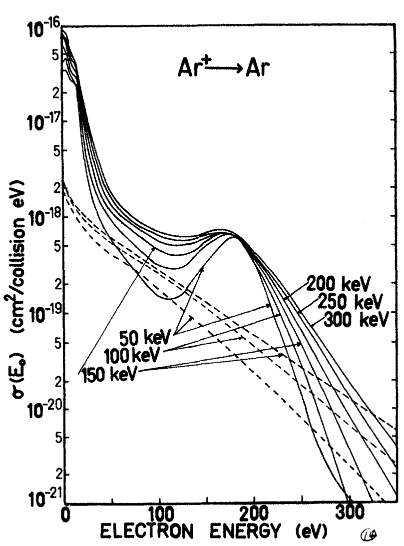

FIG. 7. Differential electron-production cross sections of argon for different ion energies (solid curves) after integrating over all angles. The dotted curves are the results of the statistical calculations made according to the prescriptions of Refs. 2 and 3.

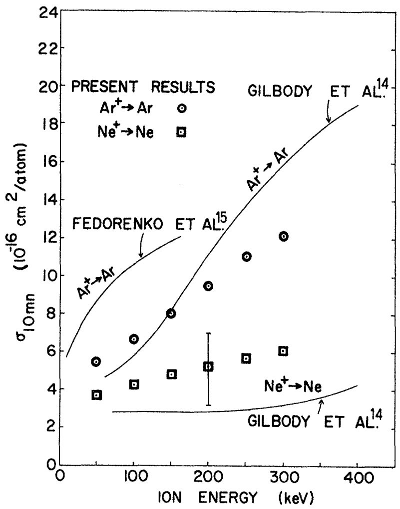

FIG. 8. Total-ionization cross sections for neon (squares) and argon (circles). Other ionization cross-section measurements of Refs. 14 and 15 are also shown.

of electrons, defined by Eq. (3), is shown in Fig. 8. The results of other groups[14,15] for electron-production cross sections is also indicated. The present results for argon agree favorably with those of Gilbody *et al.*[14]; however, the results of Fedorenko *et al.* are higher than either of these. The present neon results are as much as a factor of 2 higher than those of Gilbody. This is not considered excessive since the present results were obtained by an integration over the numerous low-energy electrons. A large contribution to the cross section comes from low electron energies where the data is the most unreliable.

The total cross section increases with increasing ion energy over the range of ion energies that were measured.

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*Present address: Department of Physics, University of Western Ontario, London 72, Ontario, Canada

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Emission of Auger Electrons Resulting from Symmetric Argon and Neon Ion-Atom Collisions

R. K. Cacak*

Department of Physics, University of Nebraska, Lincoln, Nebraska 68508

and

Q. C. Kessel

Robert J. Van de Graaff Laboratory, High Voltage Engineering Corporation, Burlington, Massachusetts 01803

and

M. E. Rudd

Department of Physics, University of Nebraska, Lincoln, Nebraska 68508

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Cross sections for the emission of Auger electrons from excited atoms and ions produced in symmetric Ar^+-Ar and Ne^+-Ne collisions have been measured at ion energies from 50 to 300 keV. A simple model is proposed to explain the dependence of the cross section on the impact energy; the predicted results agree well with the experiment. Also, the argon x-ray data of Saris and Onderdelinden are compared with the model and with the results of this experiment.

I. INTRODUCTION

Much structure has been observed[1,2] on the energy spectra of electrons resulting from energetic argon and neon ion-atom collisions. This structure appears to be superimposed upon a continuous distribution of electrons and is attributed to various autoionizing and Auger transitions within the collision partners. The purpose of this paper is to analyze the measured cross sections for exciting certain inner-shell vacancy levels by measuring the numbers of the ejected Auger electrons. Argon and neon atoms were excited by ion-atom collisions in the energy range 50–300 keV. The Auger emission cross sections have been determined by using the data of the previous paper,[3] and the experimental apparatus is described elsewhere.[4] Only the Auger transitions resulting from initial K-shell vacancies in neon and L-shell vacancies in argon have been considered. These are the strongest