Electron Energy Spectrum from Ar^+-Ar and H^+-Ar Collisions*

M. E. RUDD, T. JORGENSEN, JR., AND D. J. VOLZ
Department of Physics, University of Nebraska, Lincoln, Nebraska

(Received 30 June 1966)

Absolute differential cross sections have been measured for the ejection of electrons of various energies at 160° by argon ions and protons striking argon gas as a target. The observed energy spectrum consists of a number of "lines" or peaks superimposed on a continuous spectrum. The fine-structure regions occur below 20 eV and from about 120 to 220 eV for both projectiles. A number of lines are identified with auto-ionization transitions from neutral states and with Auger transitions from one- and two-vacancy states. With argon ions each peak has a "Doppler"-shifted counterpart due to electrons emitted from the moving particles. The data are compared with the Fano-Lichten electron-promotion model and with the statistical theories of Russek and of Everhart and Kessel.

I. INTRODUCTION

COINCIDENCE measurements by Afrosimov *et al.*[1] and by Everhart *et al.*[2] of the heavy ions resulting from Ar^+-Ar collisions have stimulated various interpretations. Russek[3] had previously proposed a semistatistical theory in which the collision produces an excitation in each atom which is followed by an auto-ionization transition in which the excitation energy is distributed statistically among the M-shell electrons. One of the consequences of this model is a continuous distribution of energies of the emitted electrons. Fano and Lichten,[4] on the other hand, suggest that the primary mechanism of energy dissipation is through the formation of an excited molecular ion followed by auto-ionization or Auger processes. These authors predict peaks in the electron spectrum near 200 eV due to Auger electrons and numerous peaks in the region below 25 eV due to auto-ionization electrons. In a pair of papers Kessel and Everhart[5] present additional data and a new interpretation which combines features of both previous models. According to them, part of the inelastic energy goes to produce a single fast electron (the energy of which is predicted to be about 200 eV), the rest of the energy being distributed statistically among the other electrons.

Since the distribution of energy among the ejected electrons differs in the various interpretations, the energy spectrum of electrons resulting from the collisions should be a crucial test of the theories. Presented here are measurements of the energy spectrum of electrons from Ar^+-Ar collisions measured at an angle of 160° from the beam. Also, since the excitation mechanism for proton bombardment would be expected to differ from that for Ar^+ bombardment, data are also included on protons for comparison.

II. DESCRIPTION OF THE EXPERIMENT

The apparatus used was similar to that described elsewhere,[6,7] so only a brief description will be given here. The ion beam is magnetically selected after acceleration and passes through the target gas (argon) which is at pressures of 1 to 6×10^{-4} Torr. The primary beam is collected and read on an electrometer or integrated. Electrons which are ejected at an angle of 160° from the ion beam enter a parallel-plate electrostatic analyzer and those within the energy resolution of the analyzer are detected by an electron multiplier. After amplification the electron pulses go to a counting-rate meter. The voltage on the analyzer is swept at a

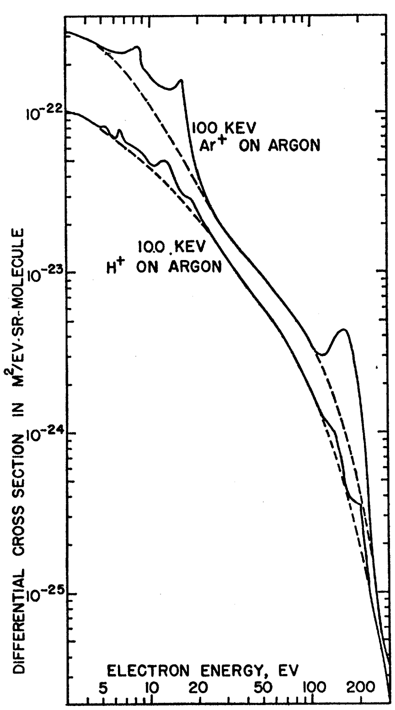

FIG. 1. Doubly-differential cross-sections for ejection of electrons from argon by protons and argon ions at 100 keV. Electrons are detected at 160° from the beam direction. Resolution varies from 0.5 eV at 3 eV energy to 12 eV at 300 eV.

* Work supported by the National Science Foundation.

[1] V. V. Afrosimov, Yu. S. Gordeev, M. N. Panov, and N. V. Fedorenko, Zh. Tekhn. Fiz. **34**, 1613 (1964); **34**, 1624 (1964); **34**, 1637 (1964) [English transl: Soviet Phys.—Tech. Phys. **9**, 1248 (1965); **9**, 1256 (1965); **9**, 1265 (1965)].

[2] E. Everhart and Q. C. Kessel, Phys. Rev. Letters **14**, 247 (1965); Q. C. Kessel, A. Russek, and E. Everhart, *ibid.* **14**, 484 (1965).

[3] A. Russek, Phys. Rev. **132**, 246 (1963).

[4] U. Fano and W. Lichten, Phys. Rev. Letters **14**, 627 (1965).

[5] Quentin C. Kessel and Edgar Everhart, Phys. Rev. **146**, 16 (1966); Edgar Everhart and Quentin C. Kessel, *ibid.* **146**, 27 (1966).

[6] M. E. Rudd and T. Jorgensen, Jr., Phys. Rev. **131**, 666 (1963).

[7] M. E. Rudd, Rev. Sci. Instr. **37**, 971 (1966).

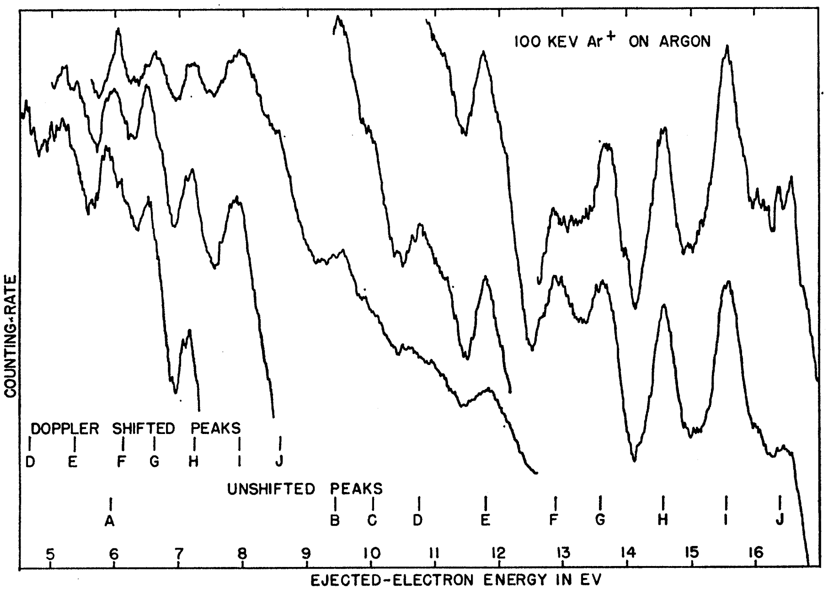

FIG. 2. Energy spectrum of electrons from 100-keV Ar^+-Ar collisions. Resolution about 0.2 eV.

constant rate and the output of the counting-rate meter is plotted versus the sweep voltage (which is equal to the electron energy) on an X-Y recorder.

For the measurements of cross sections, the electrons are counted by a scaler as in earlier work.[6] However, no correction for absorption of electrons by the target gas was made here since the gas pressure was such that the greatest absorption was about 4%.

The earth's magnetic field was annulled by three mutually perpendicular pairs of 4-ft-diam Helmholtz coils. The target gas pressure was read by an RCA 1949 ionization gauge which was calibrated with a McLeod gauge. No correction was made for the pumping action of the cold trap. The previously measured[6] value of 0.78 for the efficiency of the electron multiplier was used in the calculations of cross sections.

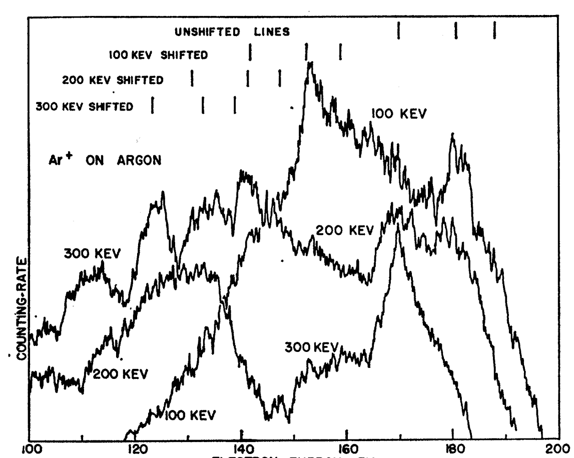

FIG. 3. Energy spectrum of electrons from Ar^+-Ar collisions. Resolution about 3 eV.

The relative values of the cross sections are uncertain by about 15%, but because of additional uncertainties in the detector efficiency and in the pressure measurement the absolute values of the cross sections have an uncertainty of 50%.

III. EXPERIMENTAL RESULTS AND DISCUSSION

In Fig. 1 are plotted the absolute differential cross sections for ejection of electrons from argon gas by protons and by argon ions. The cross section for argon ions is greater at all ejection energies. A notable feature of both curves is the fine structure between 120 and 220 eV and below 20 eV which is superimposed on the continuous spectrum of energies. These regions clearly show the Auger and auto-ionization peaks predicted by Fano and Lichten.[4] Figures 2–5 show the results of a more detailed investigation at higher resolution of the two fine-structure regions for the two types of projectiles.

In the case of argon-ion bombardment, the recently reported "Doppler" shift[8] is seen. Electrons from both the target and the incident particles are seen in approximately equal numbers. Characteristic peaks in the spectrum from the moving particles are shifted from those seen from the relatively stationary target particles. (See Fig. 2.) From a simple velocity vector triangle it is easily seen that the relation between E', the energy of the electron observed in the laboratory frame of reference, and E, the energy in the emitter's frame, is

$$E=E'-2(E_2E'm/M)^{1/2}\cos\theta+E_2m/M\,, \qquad (1)$$

where m and M are the masses of the electron and emitting atom, respectively, θ is the angle of observa-

[8] M. E. Rudd, T. Jorgensen, Jr., and D. J. Volz, Phys. Rev. Letters **16**, 929 (1966).

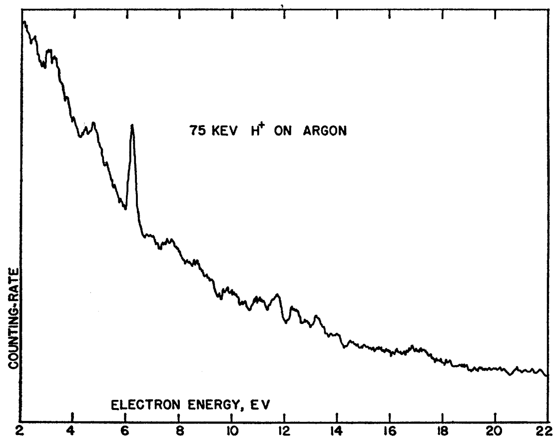

FIG. 4. Energy spectrum of electrons from 75-keV H^+-Ar collisions. Resolution about 0.2 eV.

tion, and E_2 is the beam energy. In this work, $M/m = 1836\times 40$ and $\cos\theta = -0.940$. This equation assumes that the incident particle does not lose any energy and is not deflected by the collision. While this is not true, it is a good approximation for all collisions except those with very small impact parameters.

Figure 2 shows a number of peaks in the energy spectrum plus a number of shifted peaks. Marked on the graph are the energies of the shifted peaks calculated from the measured unshifted energies using Eq. (1). These agree very well with the positions of the experimental peaks. Similar good agreement exists for measurements at 50 and 150 keV.[8]

The Doppler shift is also seen in the Auger-electron spectrum in Fig. 3. Three more or less clearly identifiable peaks and their shifted counterparts appear for each incident energy. The 181-eV peak which is most prominent at 100 keV, less so at 200 keV, and barely visible at 300 keV, is tentatively assigned to the $L_{2,3}M_{2,3}(^1D,^3D) \rightarrow M_{2,3}{}^3+1e$ transition. The 170-eV peak, conversely, is most prominent at the highest beam energy. This peak as well as the 181-eV peak could be due to a number of possible transitions all having nearly the same energy. It is not possible at this point to decide among them. The entire region from about 120 to 220 eV appears to consist of a very large number of lines too close together to be resolved in the present work. Future work planned with higher resolution may be able to separate a number of these lines for more positive identification.

It appears certain, however, that the 181-eV peak cannot be due to a transition from a single vacancy state since no such transition would result in an energy in the vicinity of 181 eV. Thus the collisions must be exciting multivacancy states. This is consistent with Kessel and Everhart's observation of argon ions in many different charge states.[5]

The lower energy fine-structure region in the H^+-Ar collisions is shown in Fig. 4. Most prominent is the 6-eV peak reported earlier.[9] This peak, the origin of which is unknown, appears also with the Ar^+ bombardment (line "A" in Fig. 2) but is comparatively much weaker than with proton bombardment. The $(3s3p^63d)^1D \rightarrow (3s^23p^5)^2P+1e$ transition occurs at 11.8 eV in both the Ar^+ and H^+ work. The energy of the initial state for this transition is given as 27.55 eV by Simpson, Chamberlain, and Mielczarek.[10] Subtraction of the ionization potential of argon yields the energy measured here.

Figure 5 shows a portion of the high-energy spectrum for H^+ incident particles. Four peaks are identified with six Auger transitions from single-vacancy states as marked on the graphs.

The existence of the Auger peaks around 200 eV and the low-energy auto-ionization peaks provides striking confirmation of the predictions made on the Fano-Lichten model. Snoek *et al.*[11] have already concluded that a purely statistical model is inadequate since it does not explain the results of their measurements of electron spectra from Ar^+-Au and Ar^+-Cu collisions. The present work confirms this conclusion since the modified statistical theory[5] does not explain the low-energy fine structure seen here and the statistical theory[3]

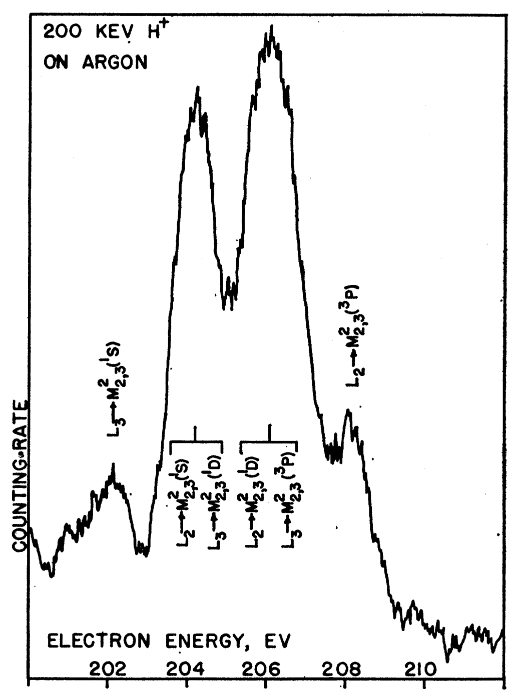

FIG. 5. Energy spectrum of electrons from 200-keV H^+-Ar collisions. Resolution about 1.4 eV.

[9] M. E. Rudd and D. V. Lang, in *Proceedings of the Fourth International Conference on the Physics of Electronic and Atomic Collisions, Quebec, 1965* (Science Bookcrafters, Hastings-on-Hudson, New York, 1965), p. 153.

[10] J. A. Simpson, G. E. Chamberlain, and S. R. Mielczarek, Phys. Rev. **139**, A1039 (1965).

[11] C. Snoek, R. Geballe, W. F. v.d. Weg, P. K. Rol, and D. J. Bierman, Physica **31**, 1553 (1965).

provides for neither the low-energy nor the high-energy fine structure.

Since the spectrum shows a line structure superimposed on a continuum, it is likely that there are at least two mechanisms operating. The line spectrum seems to result quite naturally from the Fano-Lichten model of electron promotion. The continuum is reasonably well fitted in the case of H^+-H_2 and H^+-He collisions[12] by scaling from calculations made on the Born approximation assuming Coulomb interactions and using hydrogen wave functions. It is likely that this collisional ionization is the mechanism for the continuum in the argon spectra as well.

The various theoretical treatments[3–5] concern themselves only with small impact-parameter (violent) collisions and the total cross section for such collisions is only a small fraction (perhaps a few percent) of the total cross section for ionization.[13] Therefore, it is difficult to determine whether the violent collisions contribute anything to the cross section in the continuum as envisioned in the statistical theory or whether such collisions populate only the fine-structure regions. Presumably, this question could be settled by counting only electrons which are in coincidence with projectile particles which had been deflected appreciably by the collision. We are presently pursuing this approach.

[12] M. E. Rudd, C. A. Sautter, and C. L. Bailey, preceding paper, Phys. Rev. **151**, 20 (1966). See also Ref. 6. However, this earlier work contained an error in the scaling procedure which has now been corrected.

[13] We wish to thank Professor Everhart for clarifying this point for us and for supplying data from which this estimate was made.

ACKNOWLEDGMENTS

We wish to thank Professor Everhart and Professor Fano for stimulating and helpful discussions and Alan Edwards for assistance in taking the cross-section data. Some of the data reported here were taken at Concordia College, Moorhead, Minnesota while one of us (M.E.R.) was on the staff there.

PHYSICAL REVIEW VOLUME 151, NUMBER 1 4 NOVEMBER 1966

Modified Optical-Potential Approach to Low-Energy Electron-Helium Scattering*

ROBERT T. PU AND EDWARD S. CHANG
Department of Physics, University of California, Riverside, California
(Received 9 May 1966)

A modified optical-potential approach is introduced for electron-atom scattering at low energies whereby the formal optical potential is used directly in a variational expression for scattering phase shifts. This approach has the advantage that one may include the effect of the second-order optical potential without recourse to the usual adiabatic approximation. The diagrammatic approach associated with the present method makes it possible to identify different contributing terms with different physical effects, and thus to assess the relative importance of various physical effects involved in the scattering process. To test the approach as a practical method for low-energy electron-atom scattering, we applied it to the case of electron-helium scattering for the energy range 1.2 to 16.4 eV. Good agreement with available experimental data has been obtained. The contributions of various multipole components in the second-order optical potential are examined. In particular, the effect of exchange in the second-order optical potential, neglected in most calculations, was found to be very significant.

INTRODUCTION

IN the theoretical calculation of electron-atom scattering at low energies, the difficulty is well-known to be one of complexity. That is, the problem one faces is to make suitable approximations to the solution of the complicated, but known, many-body Schrödinger equation so that good results may be obtained with reasonable effort. From a physical point of view, the approximation scheme must take into account two important physical effects, the exchange effect and the distortion effect. The exchange effect arises from the Pauli principle between the incident electron and the atomic electrons. In general, this is taken into account in theoretical calculations by explicitly antisymmetrizing the trial solution. The distortion effect, or polarization effect, arises from the distortion experienced by the atomic electrons in the presence of the incident electron's Coulomb field. The distortion or polarization of the target atom in turn produces a potential on the scattering electron. When the scattering electron is stationary, or moving slowly, the atomic electrons will polarize and adjust adiabatically to the position of the scattering electron. At large distances the dominant polarization potential is the dipole potential $-\alpha/r^4$, where 2α is the polarizability of the atom. This is the familiar adiabatic condition usually assumed for low-energy scattering processes.[1] The validity of the adia-

* Research supported in part by the National Science Foundation and the National Aeronautical and Space Agency.

[1] H. S. W. Massey, Rev. Mod. Phys. **28**, 199 (1956).