Energy Spectrum of Electrons Emitted from Gases Bombarded by Positive Ions*

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(Received December 11, 1957)

The energy spectrum of electrons ejected during ionization of neon, argon, and krypton by bombardment with potassium ions has been experimentally determined. Energy selection was effected by the focusing property at 180° of a uniform magnetic field.

The observed spectra consist of a structure of maxima and minima characteristic of the bombarded gas. The relative heights but not the positions of the maxima are functions of the incident ion energy.

INTRODUCTION

IONIZATION of gases by relatively low-energy positive ions has been studied by a number of investigators,[1–4] but little attention has been given to the energy distribution of the ejected electrons. Rouse[5] found indications of relatively high-energy ionization electrons, but in a later experiment he was unable to detect electrons of more than two ev. In a previous experiment,[6] evidence was found for ionization electrons of higher energy. The energy spectrum contained a structure of maxima and minima characteristic of the bombarded gas. However, the apparatus used was not primarily designed to measure the electron energy, and the results were presented as tentative. This paper describes a subsequent experimental investigation of the electron energy distribution.

EXPERIMENTAL APPARATUS

The electron spectrometer and the ion gun are shown schematically in Fig. 1. In order to isolate the experimental region from ferromagnetic materials, the ion gun and baffle system are supported by a cover plate at the top of a four-foot long stainless steel cylinder. The ion gun, baffle system, and Faraday cages are also of stainless steel and are gold-plated to reduce contact potentials, electrostatic charging, and secondary emission. Aluminum gaskets are used for metal-to-metal seals.

A 300 liter/sec metal mercury diffusion pump in conjunction with a dry ice-acetone vapor trap is used to evacuate the system to 6×10^{-6} mm Hg before the experimental gas is introduced. Prolonged baking of the spectrometer at 120°C is accomplished with electrical heating tape. The maximum bake-out temperature is limited by the instability of gold plating on stainless steel.

The experimental gas is drawn from high-pressure metal cylinders. The principal gas impurity is nitrogen which is present to about 2 parts in 10^4. Since nitrogen is less readily ionized by potassium ions than are the inert gases, this amount of nitrogen impurity is considered negligible. According to the manufacturer's analysis, other impurities are present only to a few parts per million. The target gas is introduced through a slow leak into the collision chamber at 10^{-3} mm Hg. At this pressure a linear increase of ionization current with pressure is observed. Continuous pumping maintains the spectrometer chamber pressure at less than 10^{-4} mm Hg.

Helmholtz coils provide the magnetic focusing field, and independent sets of vertical and horizontal Helmholtz coils are used to eliminate the earth's magnetic field.

The source of positive potassium ions is a Kunsman catalyst[7] deposited on a source S indirectly heated by a noninductive filament. Ion beams of 10^{-7} amp are drawn through two accelerating disks and collected in a Faraday cage P.

The focusing property at 180° of a uniform magnetic field is employed to observe electrons ejected with a given energy during an ionizing atom-ion collision. A 3.51-mm $\times$3.68-cm slit A in the ion gun serves as the first defining baffle. The 2.38-mm$\times$3.68-cm slit in the final baffle is placed 10 cm and 180° from the axis of the ion gun. The half-width resolving power and transmission calculated by the usual equations[8] from the spectrometer geometry are 5.8% and 1.2%, respectively.

Electrons accepted by the baffle system are collected in a Faraday cage Q connected to the input of a vibrating reedel ectrometer whose output is fed into the Y input of an X-Y recorder. The recorder X input receives a signal proportional to the magnetic field current. This method of recording data obviates the need for extreme time linearity in the magnetic-field sweep circuit.

The performance of the spectrometer was tested by initially using a barium-strontium oxide deposit instead of the Kunsman catalyst on the source disk. Thermionic electrons from this source were used to bombard gas in the collision chamber, and the number of scattered electrons reaching the signal collector Q was recorded as a function of the magnetic-field current. Curve C of Fig. 2, for example, was obtained by bom-

* Supported by the National Science Foundation.
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3 Carl Frische, Phys. Rev. **43**, 160 (1933).
4 R. N. Varney, Phys Rev. **46**, 235 (1934); **47**, 483 (1935).
5 A. G. Rouse, Phys. Rev. **52**, 1238 (1937).
6 D. E. Moe, Phys. Rev. **104**, 694 (1956).
7 C. H. Kunsman, Science **62**, 269 (1925).
8 K. Siegbahn, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), pp. 56 ff.

barding argon with 15-ev electrons. Electrons of this energy which are elastically scattered through 90° should be focussed onto Q by a magnetic-field current of 78 ma, and the observed peak at 79 ma provides reasonably good agreement with theory. The observed half-width resolving power is 6.2% compared with the calculated value of 5.8%. For electron energies below about 15 ev the resolving power tends to deteriorate with decreasing electron energy. For example, curves B and A of Fig. 2 show that the resolving power becomes 7.1% and 9.6% as the electron energy is reduced to 10 ev and 6 ev, respectively.

The ion source is heated with direct current, and experiments with reversed heater polarity produced no sensible change in line position or shape.

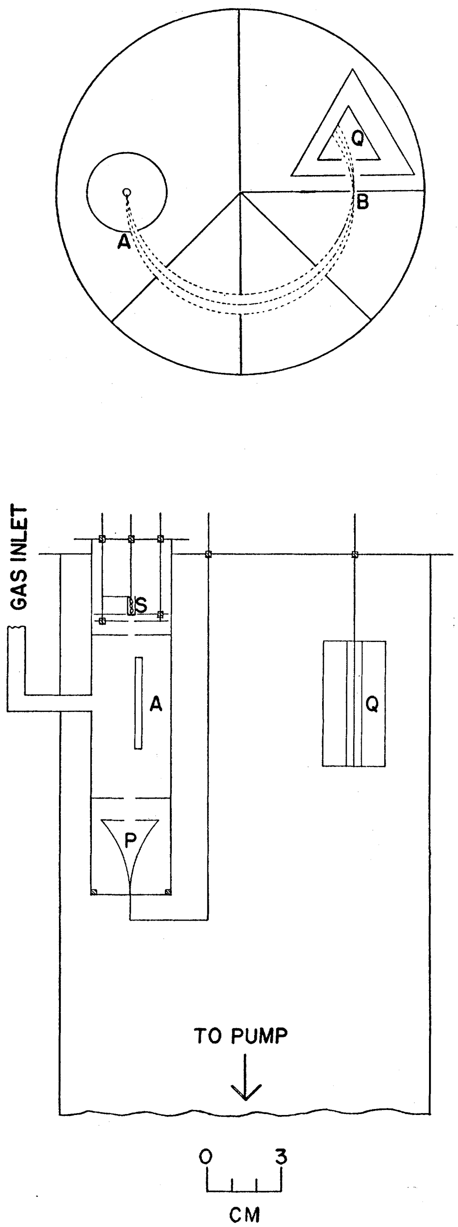


FIG. 1. Ion gun and electron velocity selector. Ions from S are accelerated into the collision chamber containing the target gas. Some electrons ejected during ionizing collisions pass through slit A in the collision chamber. A uniform magnetic field parallel to the axis of the ion gun focuses electrons of a given energy onto the electron collector Q.

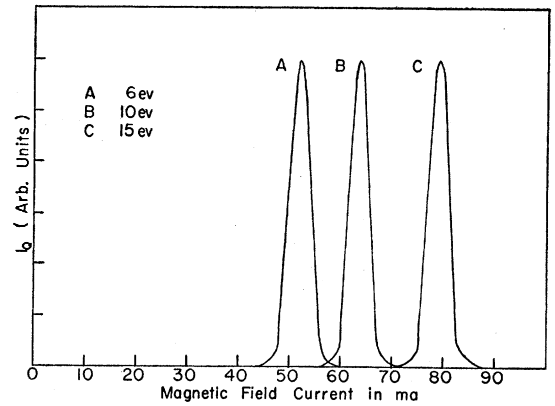


FIG. 2. Velocity spectrum of monoenergetic electrons elastically scattered from argon. I_Q is proportional to the number of electrons reaching the Faraday cage Q. Each curve corresponds to a unique energy of the incident electrons.

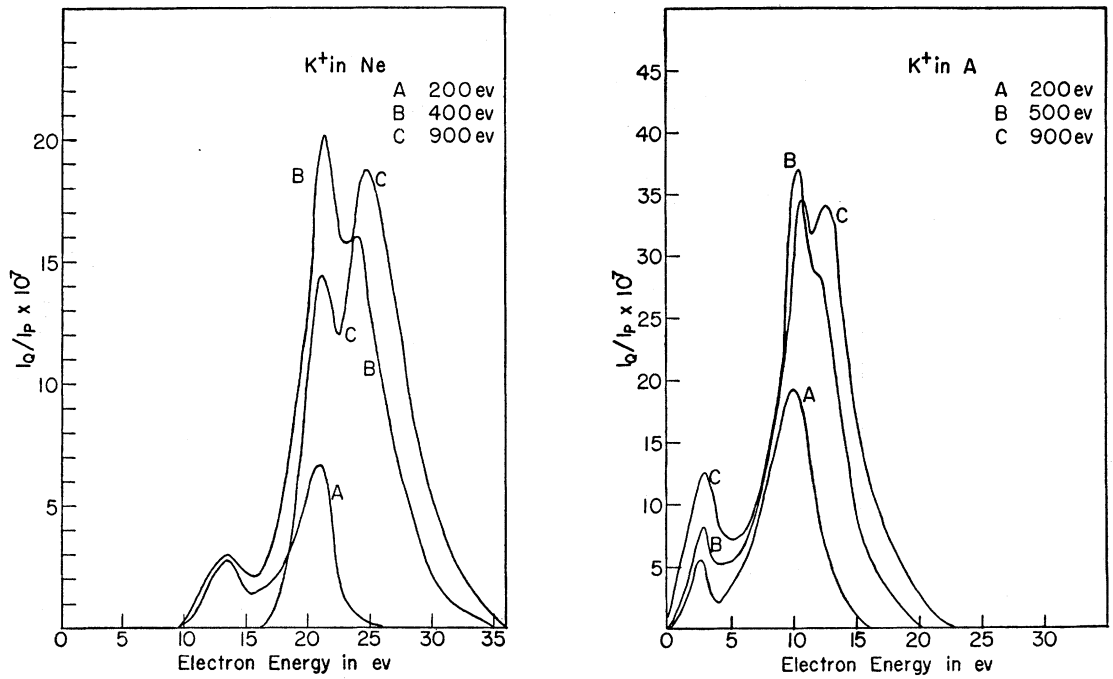
EXPERIMENTAL RESULTS

Helium, neon, argon, and krypton were in turn bombarded with potassium ions. No ionization of helium was detected. Electrical breakdown of the target gas limited ion-accelerating potentials to 900 volts. At sufficiently high ion-beam energy, ionization was observed in neon, argon, and krypton. The observed energy spectra of the ejected electrons are shown in Fig. 3. Each curve corresponds to a unique energy of the incident ion.

A structure of maxima and minima characteristic of the target gas is again observed. It is impossible to rule out completely a contribution to I_Q by secondary electrons resulting from bombardment of metal surfaces by rare gas ions or ions elastically scattered by the target gas. It seems unlikely, however, that this secondary effect represents a significant contribution to the spectra of Fig. 3. While the spectra of Fig. 3 are highly target-gas-dependent, the secondary-electron energy spectrum would be largely independent of the gas responsible for the elastic scattering. Also the published energy spectra of secondary electrons due to positive-ion bombardment of metal surfaces differ fundamentally from those of Fig. 3.[9] In particular, most secondary electrons have energies below 5 ev, while most of the electrons observed in this experiment were of energy greater than 5 ev. Finally, the observed number of electrons reaching Q is of the order of magnitude expected from published values of the ionization cross sections.

From the experimentally observed spectrometer re-

[9] M. L. E. Oliphant, Proc. Roy. Soc. (London) **A127**, 373 (1930).



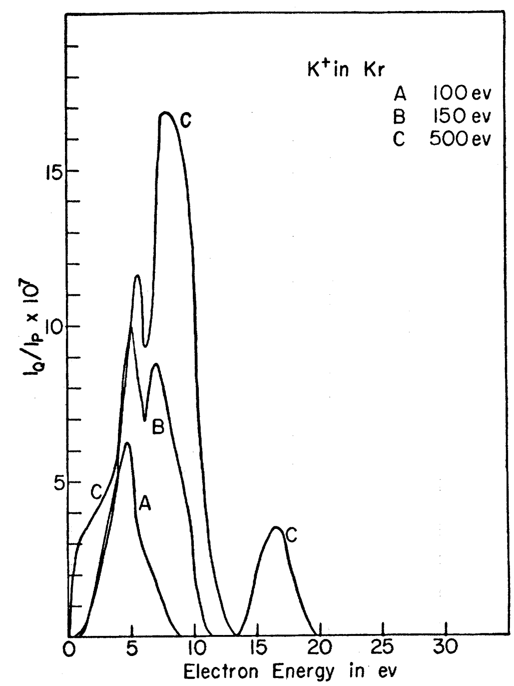


FIG. 3. Energy spectrum of electrons emitted by inert gases bombarded with potassium ions. Each curve corresponds to a unique energy of the incident potassium ions. I_Q is the electron current reaching the Faraday cage Q. I_p is the ion beam current.

solving power it was concluded that each of the separate peaks in Fig. 3 corresponds to a continuous distribution of electron energies; the width of each peak is greater than that produced by a monoenergetic group of electrons.

While the relative height of the individual peaks in Fig. 3 is a function of the incident ion energy, there is evidence that the position of each peak is independent of ion energy. It seems likely that the small observed displacement of peak position with ion energy results from the changing contribution of the tails of adjacent peaks.

It is perhaps noteworthy that the higher energy peaks appear only for the higher-energy collisions. This observation suggets that different ionization mechanisms are responsible for the different peaks, and that different ionization onset potentials exist for the individual ionization processes. Such results are in qualitative agreement with the Weizel-Beeck theory of ionization by positive ions.[10] According to the Weizel-Beeck theory, an electron is ejected by an Auger process when the ion-atom internuclear separation reaches a critical value. The critical value occurs when the electronic energy of the atom-ion system becomes equal to that of an ion-ion system. The absence of a single continuum in the curves of Fig. 3 may possibly be interpreted by the existence of more than one energy level in the ion-ion system.

A trend toward lower maximum energy of the ejected electrons as gases of progressively higher Z are bombarded is evident in Fig. 3. Extension of the investigation to other ion-atom combinations will further test this suggested correlation.

In summary, Fig. 3 presents evidence for ionization electrons of energies up to 36 ev with an energy fine structure characteristic of the target gas. As the energy of the incident ion is increased, the higher-energy peaks become more predominant, but the position of each peak remains constant. A correlation is suggested between the ionization potential of a gas and the maximum energy of the electrons ejected from that gas.

The 180° magnetic spectrometer is not inherently well suited to the measurement of absolute ionization cross sections. Only a small fraction of the ionization electrons are collected, and the collection efficiency is a function of the unknown direction distribution of the electron velocities. Nevertheless, cross sections have been calculated from the curves of Fig. 3 on the assumption of an isotropic direction distribution of electron velocities. The results are presented in Fig. 4. These values of cross sections were calculated in the following way:

1. Each ordinate of a given curve of Fig. 3 was divided by the corresponding electron energy.

2. The area of the resulting curve was divided by the product of spectrometer transmission (0.01) and the energy resolving power (0.12) to give i/I, the ratio of the total ionization current originating in the sensitive region at a given ion energy to the ion beam current.

3. The ionization cross section was then calculated

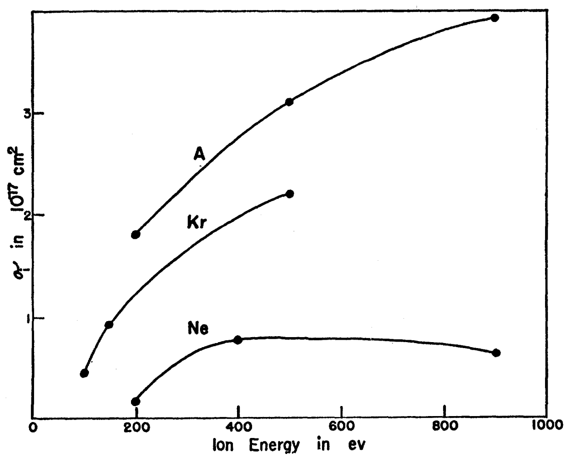


FIG. 4. Observed ionization cross sections as a function of potassium ion energy.

from the usual equation,

$$\sigma_i = i/ILpN_0,$$

where L=length of ion path in the sensitive region (3.68 cm), p=pressure in mm Hg (10^{-3} mm Hg), and N_0=number of atoms/cm^3 at 1 mm Hg pressure, a universal constant.

The curves in Fig. 4 for argon and krypton agree with the results previously observed by Moe[6] to within a factor of two. The difference is within experimental uncertainty, and the agreement suggests an isotropic direction distribution of electron emission. (The collection efficiency of the apparatus used previously was independent of direction of electron emission.)

The ionization cross section for K^+ in Ne shown in Fig. 4, however, is two orders of magnitude greater than that observed in the previous investigation. If the ionization electrons from Ne are ejected primarily perpendicular to the ion beam, the collection efficiency of the present apparatus would be abnormally high. This possible explanation of the observed discrepancy is further suggested by a comparison of the results of other investigations.[2–4] While essential agreement exists for the published cross sections for K^+ in A and Kr, the results for K^+ in Ne disagree by orders of magnitude. It is perhaps significant that whenever apparatus has been used for which collection efficiency is increased for perpendicular electron ejection, the observed cross section has been at least two orders of magnitude higher than that observed with apparatus for which the collection efficiency is independent of direction of emission.

[10] W. Weizel and O. Beeck, Z. Physik **76**, 250 (1932).