compared with the experimental values. These include, besides the Schwinger correction for the anomalous moment of the electron already mentioned, a correction to allow for deviations from pure *LS* coupling; a relativistic correction, directly related to the kinetic energy of the electrons; and a diamagnetic correction, depending on the electron density of the core.

Cabezas and Lindgren[4] in their work on Tm^{170} have shown that since the ground state of Tm is essentially a single-electron state, the effect of configuration interaction caused by spin-orbit coupling is quite negligible. By assuming the same modified hydrogenic wave function as used for obtaining the $\langle 1/r^3\rangle$ given in Sec. IV(B), they calculated the corrections to the g factor due to relativistic and diamagnetic effects. The final calculated g value, -1.14121, obtained in this way, is in excellent agreement with the experimental value.

ACKNOWLEDGMENTS

The author wishes to thank Dr. Hin Lew for his interest and encouragement in this work. He is also greatly indebted to Dr. Howard A. Shugart and his associates at the University of California for the use of their computer facilities.

PHYSICAL REVIEW VOLUME 128, NUMBER 5 DECEMBER 1, 1962

Charge Transfer between Positive Cesium Ions and Cesium Atoms*

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(Received July 16, 1962)

The cross section for charge transfer between cesium ions and cesium atoms has been determined as a function of primary ion energy from 50 to 4000 eV. At each energy the cross section was obtained from measurements of the number of slow ions formed along a known length of the fast primary ion beam in passing through cesium vapor, the primary beam current, and the number density of cesium atoms inside the interaction region. The measured cross sections are higher than those of other investigations within the same energy range in which different methods were used, but are consistent with those of an investigation in the energy range 5 to 25 keV. The result of a least-mean-squares fit indicates that the cross section may be represented between 50 eV and 4000 eV by the expression $Q^{1/2}\times 10^8=26.8-1.46\ln V$, where Q is the cross section (cm^2) and V is the primary ion beam energy (eV).

INTRODUCTION

CONSIDERABLE diversity exists between the results of a number of investigations of the resonance charge transfer reactions of the alkali metals. In this paper, results are presented for charge transfer between cesium ions and cesium atoms. These data are thought to be more reliable than those of earlier investigations within the same energy range.

Interest in cesium-ion propulsion for space vehicles and in the cesium diode as a thermoelectric device has emphasized the need for study of reactions involving cesium atoms and ions. Resonance charge transfer may be an important process occurring in both these devices. The process is represented by

$$\mathrm{Cs}^+(1)+\mathrm{Cs}(2)\rightarrow \mathrm{Cs}(1)+\mathrm{Cs}^+(2). \quad (1)$$

In the encounter the incident ion (1) captures an electron from the atom (2) with negligible momentum transfer.

In cases of resonance charge transfer, theory[1–3] predicts that the cross section at a given relative velocity increases with decrease of the ionization potential of the atom. Because of the low ionization potential of cesium, the charge transfer cross section is expected to be very large at low relative velocities of the particles. Resonance charge transfer in cesium has been investigated by Kushnir *et al.*[4,5] (KPS and KB), Bukhteev and Bydin[6] (BB), Chkuaseli *et al.*[7] (CNG), and Speiser and Vernon[8] (SV). The results of these investigations are in considerable disagreement with each other. In addition,

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* Supported in part by the Advanced Research Projects Agency (Project Defender) through the Air Force Cambridge Research Laboratory.

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[1] Yu. N. Demkov, Scientific Notes, Leningrad State University, No. 146, Issue 8, 74 (1952).

[2] O. Firsov, J. Exptl. Theoret. Phys. (U. S. S. R.) **21**, 1001 (1951).

[3] I. Flaks and E. Solov'ev, Soviet Phys.—Tech. Phys. **3**, 564 (1958).

[4] R. Kushnir, B. Palyukh, and L. Sena, Bull. Acad. Sci. U. S. S. R. **23**, 995 (1959).

[5] R. Kushnir and I. Buchma, Bull. Acad. Sci. U. S. S. R. **24**, 989 (1960).

[6] A. Bukhteev and Y. Bydin, Bull. Acad. Sci. U. S. S. R. **24**, 966 (1960).

[7] D. Chkuaseli, U. Nikoleishvili, and A. Guldamashvili, Bull. Acad. Sci. U. S. S. R. **24**, 972 (1960).

[8] R. Speiser and R. Vernon, American Rocket Society Space Flight Report to the Nation, Report No. 2068-61, 1961 (unpublished).

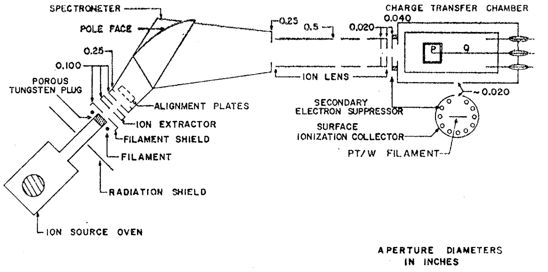

FIG. 1. Schematic diagram of the experiment.

in one of the investigations[6] it was found that the resonance charge transfer cross section of potassium was larger than that of cesium for the same relative velocity. This is contrary to Firsov's prediction.[2,3] It appears likely that the root of the disagreements in the several investigations lies in the measurement of the number density of the target cesium atoms. Consequently, in this investigation considerable emphasis was placed upon determining this quantity correctly.

EXPERIMENT

A. General Description

A schematic diagram of the apparatus is presented in Fig. 1. Cesium ions were produced by the surface ionization of atoms diffusing through a heated porous tungsten plug. These ions were then accelerated, mass analyzed, and finally focused into the charge transfer chamber. This chamber contained neutral cesium atoms whose number density was measured with a surface ionization detector. The slow ions, which resulted from charge transfer, and the primary ion beam were collected on the parallel plates P and Q, respectively, to which suitable potentials were applied. The measurement of the above quantities and certain dimensions of the electrodes allowed the cross section for a particular ion beam energy to be calculated. All the components of the apparatus were situated inside a large stainless steel vacuum chamber pumped by mercury vapor pumps and liquid nitogen-cooled traps.

B. Ion Source

The ion source oven consisted of a stainless steel block 1 in. wide, 1 in. high, and 1.5 in. long. A glass ampoule of metallic cesium was placed in a cavity bored from the top of the block. When the cap to this cavity was screwed tight, it crushed the ampoule. A horizontal channel led from the cavity to a 2-in.-long molybdenum tube of $\frac{1}{8}$-in. diameter. A sintered porous tungsten button was fixed to the tip of this tube.[9] Heater coils which were inserted through holes in the oven block raised the oven temperature to about 175°C. At this temperature, the pressure of cesium vapor in the cavity was about 2×10^{-2} mm Hg. The button was raised to a temperature, obtained by electron bombardment from a surrounding filament, sufficiently high to ionize the cesium atoms diffusing through it. A shield at the filament potential prevented the deflection of electrons away from the tip by the ion extraction field. It also discouraged electrons from bombarding the ion beam thus reducing the possibility of creating excited ions. The ion source oven and tungsten button were heated to such temperatures that any further increase did not significantly increase the ion current. The final ion energy was determined by the potential of the ion source with respect to the charge transfer chamber which was grounded. The oven rested on three quartz pins so that it was electrically and thermally insulated from the supporting base.

C. Mass Spectrometer and Ion Lens

A nonsymmetrical spectrometer[10] was employed to mass analyze the ion beam. This type of instrument focuses incident rays to very high order over large entrance angles in contrast to the symmetrical type. The latter gives only first order focusing and, therefore, the incident rays must deviate from the normal to the magnetic field only by small angles. The instrument used had a radius of curvature of 10 cm and a sector angle of 60°. The object to apex distance was 9 cm and the apex to image distance was 24 cm. It focused an incident ion beam whose maximum divergence was 25° and whose central ray entered the magnetic field boundary at an angle of 65°. In passing through the magnetic field, the ions were contained in a stainless steel box insulated from the magnet's grounded pole faces. This was necessary because the maximum magnetic field focused cesium ions of energy of about 1000 eV. A pair of parallel plates was located just inside the entrance aperture of the case. The potential across these plates could be adjusted in order to align the ion beam in planes parallel to the magnetic field.

The ion lens was constructed of 0.5-in.-diam stainless steel cylinders. Its design is straightforward[11] and was characterized by a magnification of 0.2, a 5-in. object distance, and 1-in. image distance. The ion current passing into the charge transfer chamber was typically 10^{-8} A and somewhat smaller at the lower energies.

D. Charge Transfer Chamber

The charge transfer chamber consisted of a copper block 2.125 in. square and 6 in. long. A 1.75-in.-diam hole was bored concentric with the long axis. Each end of the hole was threaded. The secondary electron suppressor and entrance aperture were mounted on a copper plate which was screwed into the front end. The electrode system was attached to another copper plate

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[9] This assembly was obtained from Semicon of California, Inc.

[10] E. T. S. Walton, Proc. Roy. Irish Acad. A57, 1 (1954).

[11] K. Spangenberg, *Vacuum Tubes* (McGraw-Hill Book Company, Inc., New York, 1948).

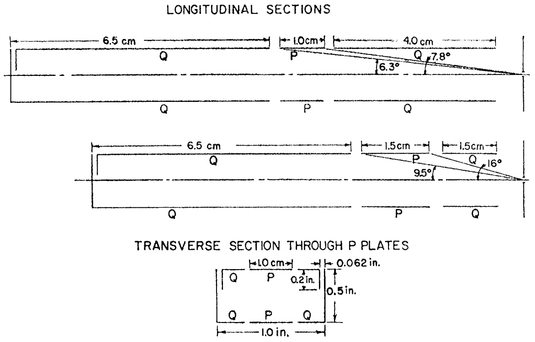

Fig. 2. Charge transfer electrode systems. The plates P collect slow ions resulting from charge transfer and plates Q measure the primary ion beam current less the P plate current.

which was screwed into the other end. The chamber and end plates were rhodium plated. A copper reservoir with a 0.625-in.-diam cavity 1 in. deep could be screwed into a hole in the bottom of the chamber. In an argon atmosphere, cesium metal was introduced into a stainless steel cup and then covered with benzene. This cup was placed in the reservoir which was then fitted to the chamber. Upon evacuating the vacuum chamber, the benzene rapidly evaporated, thus, leaving the cesium metal exposed. The vapor pressure of cesium inside the chamber was controlled by the temperature of the reservoir. Four tantalum heater coils were located in holes bored in the corners of the chamber parallel to the long axis. The chamber was mounted to a water-cooled brass base plate by four stainless steel cylinders whose dimensions were selected to make the thermal time constant of the chamber approximately 30 min. A copper strap connected between the reservoir and the base plate insured that the reservoir temperature was about 4°C cooler than any of the temperatures measured at six other points on the chamber. The charge transfer data were obtained with reservoir temperatures in the range of 50 to 75°C.

E. Electrode System

The electrode system was a modified form of that used by Stedeford[12] and is shown in Fig. 2. Two sets of electrodes were used, differing essentially only in their dimensions. The two plates marked Q were supported parallel to each other with their turned-over edges separated by a small gap, thus forming an open-ended rectangular box. Square or rectangular openings were cut in the plates immediately opposite each other. The P plates were slightly smaller than the Q plate openings in which they were placed. Equal positive and negative potentials of about 10 V with respect to ground were applied to the Q plates, and a potential equal to its surrounding Q plate was applied to each P plate. An electrometer was connected between the circuit of each pair of plates and ground. The primary ion beam entered the electrode structure along the longitudinal axis and was finally collected at the end of the box on one of the Q plates. The field across the plates was kept sufficiently small so that its effect upon the beam was negligible. Secondary electrons produced at the end of the box could not escape or strike the P plates because of the transverse field. Slow ions from charge transfer and ionization, and electrons from ionization formed along the path of the primary beam between the P plates, were drawn to the negative and positive P plates, respectively. Because only the net current to the pair of P plates was measured, the equal numbers of positive and negative charges from ionization cancelled each other leaving only the contribution from charge transfer. It can be seen readily that the net current to the Q plates was equal to the primary ion beam current entering the electrode structure less the net current to the P plates.

The nominal dimensions of the two electrode systems are also given in Fig. 2. The dimensions of the P plates and the openings in the Q plates were measured with a micrometer. The electrodes were constructed of 0.010-in.-thick stainless steel. The cross sectional dimensions were chosen by electrolytic tank plotting so that the field would be uniform across the slow ion collection (P) plates. The electrodes were held in position by 0.050-in.-diam tungsten, molybdenum or nickel rods to which they were spot welded. The ends of the rods were fixed to metal-to-glass seals which were welded or brazed into the copper end plate of the charge transfer chamber. A heater was fixed to this rear plate to prevent the leakage resistance between any electrode and the chamber from falling below about $10^{12}\,\Omega$. The rear plate was, normally, about 5°C warmer than any other point of the chamber.

F. Detector

The number density of the neutral cesium atoms inside the charge transfer chamber was determined with a surface ionization detector. Cesium atoms effused through an aperture, about 0.02 in. in diameter, in the side of the charge transfer chamber and then through a second similar aperture in the collector electrode of the detector. Each aperture was 0.005 in. thick. No Claussing correction was required, however, since the detector orifice subtended a half angle of about 1° with respect to the center of the chamber orifice and the two axes were aligned to coincide. The separation of the orifices was about 1.5 cm. After passing through the detector aperture, the atoms were ionized on the surface of a heated 92% platinum and 8% tungsten ribbon filament which was wide enough to intercept all the atoms passing through the two apertures. The ions were accelerated from the filament to the collector, which completely surrounded the filament, by a positive potential placed on the filament. This ion current was measued with an electrometer. The collector was a

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[12] J. B. H. Stedeford, Proc. Roy. Soc. (London) **A227**, 466 (1955).

copper block 1 in. square by 1.25 in. high with a 0.625-in.-diam hole bored through it parallel to the long axis. Copper covers were fitted over the top and bottom. The block and covers were gold plated. A 98% transparent grid was fixed between the filament and collector to suppress secondary electron emission from the collector due to ion bombardment. The collector was fixed rigidly to, but electrically insulated from, a 1 in. square copper bar. This bar could be attached either to a liquid nitrogen-cooled trap or to the water-cooled base plate of the charge transfer chamber.

For effusive flow through the chamber orifice the surface ionization current in amperes may be expressed by

$$I = 1.7919\times10^{3}\frac{p}{r^{2}}\frac{1}{(MT)^{1/2}}aa', \qquad (2)$$

where p is the vapor pressure in mm Hg, M is the mass number, a is the chamber orifice area in cm^2, a' is the detector orifice area in cm^2, T is the temperature in degrees Kelvin that determines the mean speed of atoms inside the chamber, and r is the distance between the orifices in cm. For cesium and with our geometry, it is found that

$$I = 3.541\times10^{-4}\, p/\sqrt{T}. \qquad (3)$$

Equation (3) may be placed in the form

$$n = 2.768\times10^{22}\, I/\sqrt{T}, \qquad (4)$$

where n is the number of atoms per cm^3 in the chamber. A small correction is included in this relation since the apparent reflection coefficient for cesium atoms incident on a Pt-W filament is about 0.015.[13] The areas a and a' of the two circular apertures were determined by projecting their profiles onto the screen of a metallograph of known magnification. Several diameters of each image were measured and the area was calculated from the mean diameter. The distance between the orifices was determined with a measuring telescope.

APPARATUS TESTS

The energy spread of the primary ion beam was investigated by measuring the current I_Q to the Q plates as a function of the retarding potential V on the secondary electron suppressor. This was done at nominal beam energies of 25, 50, 100, 500, and 1800 eV. The full width at half-maximum of the derivative dI_Q/dV plotted against V was about 3% of the primary ion beam energy for all of the beam energies investigated.

Various tests of the atom detector were performed. The positive ion current to the collector was measured as a function of filament current and a typical plot is shown in Fig. 3. The operating current was chosen well above the knee of the curve. The possibility of obtaining collector currents greater than that corresponding to the particle density inside the charge transfer chamber was investgated. This could happen in two ways, secondary electrons may be emitted by the collector upon the impact of cesium ions, and neutral cesium atoms evaporated from the collector walls may be reionized. Accordingly, the suppressor grid and provision for cooling the collector were installed. The results of this investigation are presented in Fig. 4. No reduction of detector current was observed when the collector was cooled, which indicated that reionization of cesium atoms was negligible. Secondary electron emission from the collector increased with filament potential and was greater when the collector was cooled. The cross-section data were taken with the collector at room temperature, with the filament 50 V positive with respect to the collector, and with the collector connected to the grid.

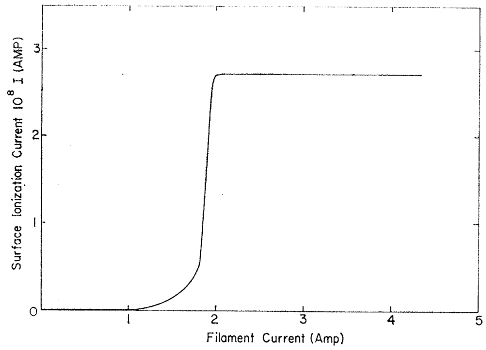

FIG. 3. Typical curve used to determine the atom detector filament current which was required to insure that all the incident atoms were surface ionized.

It was decided to measure the vapor pressure of cesium since the existing data are not in agreement. Figure 5 presents the results of this investigation together with two previous determinations. The vapor pressure was computed from Eq. (3). The temperature used in this equation was that of the reservoir.

Our results agree with those of Taylor and Langmuir.[14] The solid curve was computed from their relation

$$\log p = 11.0531 - 1.35\log T - 4041T^{-1}, \qquad (5)$$

where p is expressed in mm Hg and T in degrees Kelvin. Kelley's curve[15] is about 30% lower than the Taylor and Langmuir result. His work is a review of various vapor pressure data available at that time. He obtained an expression for the vapor pressure from the data of six different investigations. In the units adopted here the expression becomes

$$\log p = 11.8007 - 1.53\log T - 4206T^{-1}. \qquad (6)$$

The dot-dash curve in Fig. 5 was calculated from this equation. In obtaining our vapor pressure data, it was observed that several days of heating the charge transfer chamber at a given temperature were required in order

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[13] S. Datz and E. Taylor, J. Chem. Phys. **25**, 389 (1956).

[14] J. Taylor and I. Langmuir, Phys. Rev. **51**, 753 (1937).

[15] K. K. Kelley, U. S. Bur. of Mines, Bull. 383 (1935).

for the surface ionization current to reach a steady value. This period of heating was only necessary immediately after a new charge of cesium had been placed in the reservoir and was possibly due to slight impurities present or introduced in the handling procedure.

The possibility of pressure differences existing between the ends and the middle of the chamber was investigated by placing another detector at one end of the chamber. The two detectors indicated no observable difference in pressure.

PROCEDURE

The primary ion beam is attenuated through charge transfer in the region between the electrodes according to the relation

$$I=I_0e^{-nQx}, \qquad (7)$$

where I_0 and I are the beam currents at the beginning and end, respectively, of a path length x measured along the beam direction, n is the number density of cesium atoms, and Q is the charge transfer cross section. The ratio of the net slow ion current collected at the P plates due to charge transfer to the total ion current (due to both slow and fast ions) to the Q plates is

$$\frac{I_P}{I_Q}=\frac{1-e^{-nQl}}{e^{nQl_1}+e^{-nQl}-1} \qquad (8)$$

where l is the interaction length over which the ions comprising I_P are formed, l_1 is the interaction length over which slow ions are formed between the front of the Q electrodes to the midpoint of the front gap between the P and Q plates. Equation (8) may be written in the form

$$I_P/I_Q=nQlf. \qquad (9)$$

In this expression f is given by

$$f=\sum_{m=0}^{\infty} c_m x^m, \qquad (10)$$

where

$$c_m=(a_m-b_1c_{m-1}-b_2c_{m-2}\cdots-b_mc_0)/(b_0-1), \qquad x=nQl, \qquad (11)$$

and

$$a_m=(-1)^m/(m+1)!, \quad b_m=[L^m+(-1)^m]/m!, \qquad L=l_1/l. \qquad (12)$$

To an accuracy such that the higher order terms are not significant to the third decimal in f (for the values of L used here),

$$f=1-\frac{1}{2!}(2L-1)nQl+\frac{1}{3!}[3L(L-3)+1](nQl)^2 -\frac{1}{4!}[4L^3-42L^2+28L-1](nQl)^3. \qquad (13)$$

The ratio I_P/I_Q as a function of f is given in Fig. 6 for the two electrode systems.

From Eqs. (4) and (9) we obtain

$$I_P/I_Q=(2.768\times10^{22}Ql)fI/\sqrt{T}. \qquad (14)$$

At a given primary beam energy, the ratio I_P/I_Q was measured at a number of cesium atom densities in the charge transfer chamber. Figure 7 presents a typical

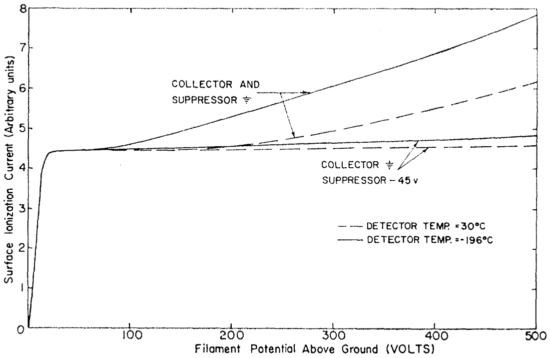

FIG. 4. Detector performance showing the difference between the cooled and warm detector. Evaporation of atoms from the collector with subsequent reionization on the filament is not significant. The effect of secondary electron emission especially from the cooled (−196°C) collector is evident.

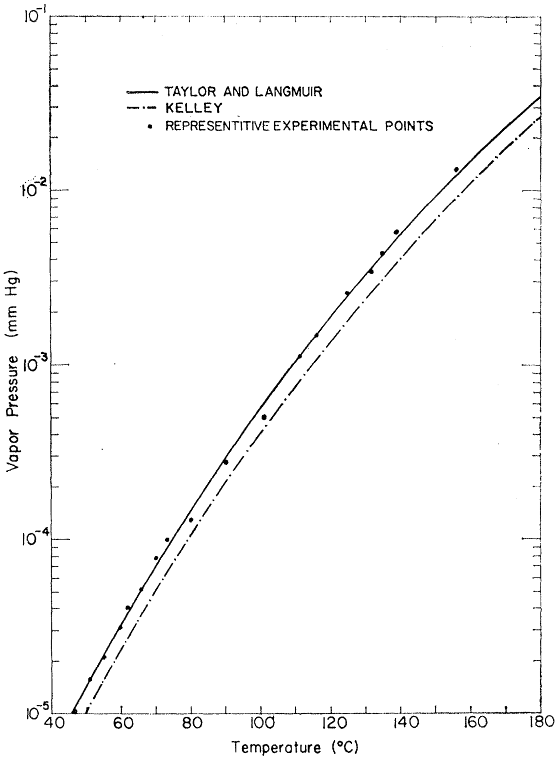

FIG. 5. Vapor pressure of cesium as a function of temperature. Good agreement between our data and the Taylor and Langmuir result (see reference 14) is noted. Kelley's result was obtained from a review of the work extant at the time (see reference 15).

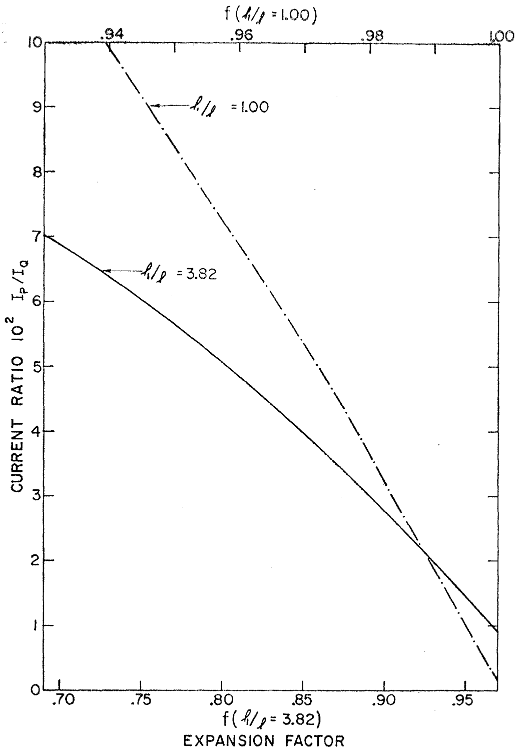

FIG. 6. Curves used to obtain the factor f arising from the expansion $I_P/I_Q=(1-e^{-nQl})/(e^{nQl_1}+e^{-nQl}-1)=nQlf$, where l is the length over which ions comprising the P plate current (I_P) are formed and l_1 is the length over which slow ions are formed between the front of the Q plates to the midpoint of the front gap between the P and Q plates, I_Q is the current to the Q plates, n is the atom number density, and Q is the charge transfer cross section. Note that f is much closer to unity for the curve corresponding to the electrode system characterized by $l_1/l=1.00$ than for that in which $l_1/l=3.82$.

plot of I_P/I_Q as a function of $fI/\sqrt{T}$ [which is related to the density through Eq. (4)] for a primary beam energy of 3500 eV. Knowing l, the cross section may be obtained from the slope of this line. As mentioned earlier, collection potentials symmetric with respect to ground were applied to the P and Q plates. These potentials were chosen so that all of the slow ions formed between the P or Q plates were collected by them. The potentials required with a particular primary ion beam energy were determined from a collection curve such as the one shown in Fig. 8.

In order to be certain that no secondary electrons arising from impact of the fast ion beam upon the Q plates were collected by the P plates, the charge transfer chamber could be immersed in a magnetic field of up to 450 G (but typically 75 G). Its direction was perpendicular to the P plates. It was found that this field had no effect on the slope of the straight lines obtained in plots typified by Fig. 7. Most of the data were taken without the magnetic field.

Not shown in Fig. 1 is a magnetic shield which was placed between the ion lens and the spectrometer. It also served as a light shield between the ion source and the charge transfer chamber. It was found necessary to shield the three viewing ports in the vacuum chambers in order to eliminate an effect which was attributed to photoionization of cesium in the charge transfer chamber.

Elastic scattering of the ion beam by the cesium vapor in the charge transfer chamber would also be measured by the electrode system if the scattering angles were large enough (see Fig. 2). The total elastic scattering cross section for ions was estimated[16] and found to be about an order of magnitude larger than the charge transfer cross section in the energy range of interest. Thus if it is desired to prevent elastic scattering from making a contribution greater than 1% of the charge transfer scattering, the resolution of the electrodes must be poor enough so that the ratio $Q_E/Q_T=10^{-3}$, where Q_E and Q_T are the experimentally determined and total ion elastic cross sections, respectively. An estimate of the resolution required to accomplish this may be obtained from the rigid sphere model of Massey *et al.*[16,17] since the de Broglie wavelengths of the ions used in the present experiment are small (less than 10^{-10} cm). The result is

$$\theta=\frac{7.07}{a}\left(\frac{Q_T-Q_E}{Q_T}\right)^{1/2}\frac{1}{(MV)^{1/2}}, \tag{15}$$

where θ is the minimum angle of deviation of the ion beam in degrees in the laboratory system for which a collision is counted if the error in the total cross section is not to exceed $1-(Q_E/Q_T)$. M and V are the mass number and energy in electron volts of the impacting species, respectively. The interaction length a was taken to be $\sqrt{2}$ times the sum of the gas kinetic radii (in angstroms) of the colliding atoms. For the above value of Q_E/Q_T, θ is about 0.015° whereas the smallest angle

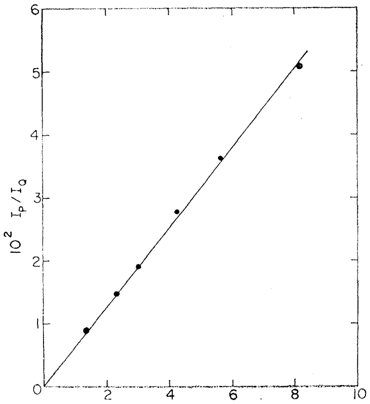

FIG. 7. Typical plot used to determine the charge transfer cross section. The slope of the line is equal to a known constant multiplied by the cross section. This plot is for a 3500-eV primary ion beam.

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[16] H. S. W. Massey and C. B. O. Mohr, Proc. Roy. Soc. (London) A141, 434 (1933); A144, 188 (1934).

[17] H. S. W. Massey and E. H. S. Burhop, *Electronic and Ionic Impact Phenomena* (Oxford University Press, New York, 1952).

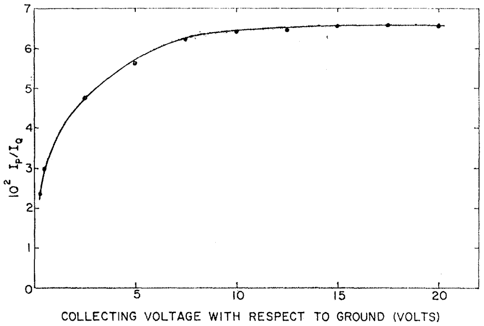

FIG. 8. Typical curve used to determine the electrode potentials required to insure saturation of the slow ion current. Curves of this type, illustrated here for a 2000-eV primary ion beam, were taken for all primary ion beam energies.

to the P plates is 6.3° (see Fig. 2). This indicates that the effect of elastic scattering should be negligible.

The contribution of elastic scattering was also examined experimentally by means of the two electrode systems. If we assume that the differential cross section is constant at the relatively large angles required to scatter ions to the P plates, then the elastically scattered intensity measured by them is proportional to the integrated angle which they subtend from the scattering centers along the ion beam path. The result is that the electrode system with the 1.5-cm P plates (see Fig. 2) should collect about 50% greater scattered intensity. Both electrode systems yielded identical cross sections within the experimental uncertainty, indicating that elastic scattering had a negligible effect compared with charge transfer collisions.

RESULTS AND DISCUSSION

The cross sections which were obtained are presented in Fig. 9 together with the results of the previous investigations. The curve marked "present result" was obtained by a least-squares fit of 52 datum points plus the 7 datum points of CNG[7] to an equation of the form[1,18]

$$Q^{1/2}=a-b\ln V, \tag{16}$$

where $a=27.2\times10^{-8}$ and $b=1.53\times10^{-8}$ for Q in cm² and V in eV. If only our data are analyzed, we obtain $a=26.8\times10^{-8}$ and $b=1.46\times10^{-8}$. The two curves are virtually indistinguishable between 50 and 4000 eV. The 6% uncertainty shown in Fig. 9 is two times the standard error. In addition, a systematic probable error of 3% could be present due mainly to uncertainty in the interaction length l. KPS[4] and KB[5] state that their results are accurate to 10%, exclusive of the uncertainty in determining the vapor pressure, which was calculated from measurements of the reservoir temperature. They estimated this uncertainty to be about 15%. It is felt that the error could be much larger than this and could account for the difference between their cross sections and those of the present investigation. BB[6] measured the cross section in terms of the resonance charge transfer cross section of potassium. This latter cross section was measured in the same paper and depended upon the calculation of the vapor pressures of potassium from measured temperatures. They state that their accuracy is 15%. Again it seems probable that the error arises chiefly from the indirect method of measuring the number density of cesium atoms. The curve marked SV was obtained from an experiment[8] in which the ion beam intersected a thermal neutral beam at right angles The cross section was obtained from the relation

$$Q=(I_s\bar{v}d)/(I_fI_a), \tag{17}$$

where I_s is the slow ion current measured by a pair of electrodes above and below the interaction region and

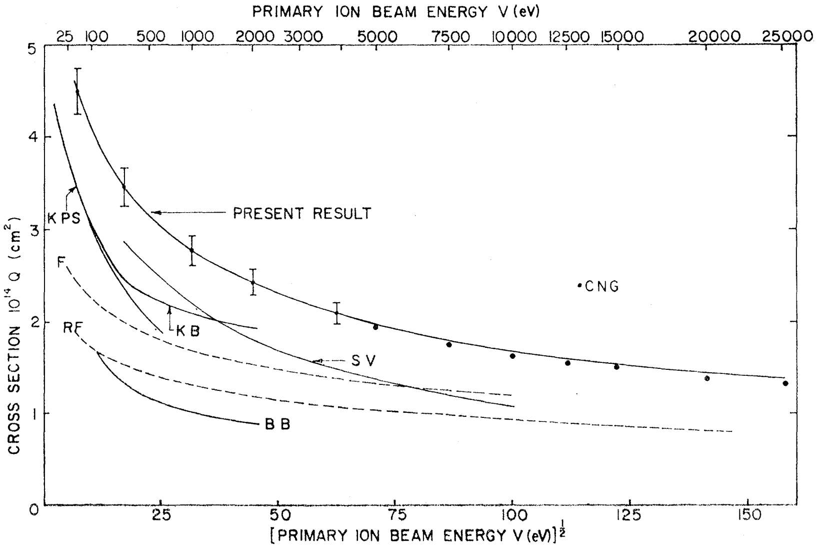

FIG. 9. Cesium resonance charge transfer cross section as a function of primary ion beam energy. Experimental results are identified by solid curves and points (see references 4 to 8). The two dashed curves are theoretical predictions (see references 2 and 20). While fifty-two datum points were obtained between 50 eV and 4000 eV, error bars are shown only for representative primary ion beam energies. The curve marked "present result" was obtained by a least-squares method using our data and the seven points of CNG (see reference 7). If only our data are analyzed, the curve obtained is virtually indistinguishable from that shown in the figure.

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[18] A. Dalgarno, Phil. Trans. Roy. Soc. (London) **A250**, 426 (1957-1958).

parallel to the two beams, I_f is the fast primary ion beam current, d is the width of the ion beam measured perpendicular to the atom beam direction, I_a is the atom current measured by a surface ionization detector whose V-shaped collector was cooled to -196°C to prevent reevaporation of the atoms, and $\bar{v}$ is the average velocity equal to $(8kT/\pi m)^{1/2}$, where T is the temperature of the atom beam oven. The average accuracy was about 10%. In the present work, it was found that cooling the collector to -196°C enhanced the secondary electron emission from it (see Fig. 4). The maximum filament to collector potential used by SV was 90 V. It is possible that secondary electron emission from the collector contributed to the detector current. This additional current would cause the cross section to appear too small. The error arising from this effect may be appreciable, but is probably too small to account for the difference between their results and ours. CNG[7] obtained the seven points plotted from 5 to 25 keV in a beam-beam experiment which utilized a small electromagnetic isotope separator for producing the primary ion beam. The neutral beam intensity was determined by measuring the deflection of a sorption detector. Simultaneously, the intensity of a small auxiliary beam was monitored with a surface ionization detector. This beam emanated from the same oven as the main beam, but was at right angles to it. Thus, a calibration curve of the main beam intensity as a function of the auxiliary beam intensity could be obtained. This was necessary since only the surface-ionization detector could be used during the charge transfer measurements. The accuracy of the results was stated to be 10% and was due primarily to the uncertainty in determining the molecular beam intensity. While it is not clear from this paper whether the average beam velocity or the average gas velocity (the correct one in this case) was used in computing the cross section, a later paper[19] on the resonance charge transfer of potassium states that the velocity was taken to be $1.18\bar{v}$, where $\bar{v}$ is the average gas velocity. Thus, the average beam velocity instead of the average gas velocity was used and was probably also employed to obtain the cross sections for cesium. The seven points plotted in Fig. 9 were obtained by reducing CNG's data by 15%.

The curves marked F and RF are theoretical estimates and both are lower than the present results. Curve F was calculated by applying Firsov's impact parameter treatment of resonance charge transfer to cesium.[2,3] Curve RF is the result of an impact parameter treatment by Rapp and Francis.[20] These treatments do not claim high accuracy. It is estimated that the uncertainties are at least 30%.

The present results are probably the most accurate obtained to date at energies up to 4000 eV. Of the previously published work only that of CNG is free of the criticisms mentioned earlier concerning the determination of the number density of the atoms in the interaction region. It is noticeable that the present results are in good agreement with those of CNG but not with those of the other investigations.

ACKNOWLEDGMENT

The authors are indebted to S. M. Trujillo for the design and construction of various electronic components of the experiment.

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[19] D. Chkuaseli, U. Nikoleishvili, and A. Guldamashvili, Soviet Phys.—Tech. Phys. **5**, 770 (1961).

[20] D. Rapp and W. Francis (private communication).