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SURVEY OF ELECTRON-CESIUM COLLISION PROBABILITIES: MOMENTUM TRANSFER COLLISIONS

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Lewis Research Center

Cleveland, Ohio

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16. Abstract
This report contains a comprehensive collection of the experimental and theoretical values of the electron-cesium atom probability of collision for momentum transfer at electron energies up to 2.0 eV. It was found that a considerable lack of agreement exists, with regard not only to the magnitude of the collision probability at a given energy, but also to the position (even the existence) of minima and maxima. Qualified recommendations of the correct values are offered.

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SUMMARY

The object of this work was to survey the literature in the field of atomic physics to determine the accuracy with which the electron-cesium atom probability of collision for momentum transfer is known. Both experimental and theoretical determinations of this probability for electron energies up to 2.0 eV were included.

The experimentally observed cross sections differ enormously in magnitude. For instance, over the range of electron velocity from 0.35 to 0.45 $(eV)^{1/2}$ the reported values of the probability differ by a factor of 100. But variations in the value of the collision cross section are only part of the disagreement which prevails. Many authors present results which show the probability of collision dropping to a low value as electron energy approaches zero, in direct contradiction of other data. Marked peaks in the cross section reported by some are frequently not observed at all in other experiments, and in some cases minima are observed.

Because of the lack of any consensus in experimental results, the theoretically computed collision probabilities could hardly agree with the measured values, but neither do they agree with each other.

The basic conclusion to be drawn is that the measurement of the electron-cesium atom probability of collision for momentum transfer is a very difficult experiment to perform. Very likely, many of the measurements now available are rather accurate, but only much careful work and replication of experiment can isolate the true value.

INTRODUCTION

The probability of collision for momentum transfer of electrons with cesium atoms is of great interest in the study of the cesium-filled thermionic converter and other electronic devices. This quantity, which we shall denote as $P_m(v)$ because it is in general a function of electron velocity, has been measured and evaluated by a number of investigators, frequently with contradictory results. The probabilities of collision for momentum transfer obtained from both measurements and calculations are presented for electron velocities up to 1.4 $(eV)^{1/2}$ (kinetic energy of 2 eV). This range includes the first excited state of cesium and covers the range of greatest interest in thermionic conversion.

SYMBOLS

a_o	Bohr radius
C	constant
e	electron charge
j	$\sqrt{-1}$
k	Boltzmann constant
l	integral constant
m	electron mass
N	neutral particle concentration
n	electron concentration
$P_m(v)$	probability of collision for momentum transfer
p_o	reduced pressure in torr, normalized to 273 K
$Q_m(v)$	collision cross section for momentum transfer
T	electron temperature
v	electron velocity
v_p	electron velocity of a monoenergetic beam, or most probable velocity in a Maxwellian distribution
$\langle v \rangle$	mean electron speed
$\overline{\nu}_m$	average collision frequency
$\nu_m(v)$	collision frequency for momentum transfer
σ	conductivity
$\langle \sigma \rangle$	effective conductivity
ω	radian frequency

Subscripts:

BL	Bohdansky and Langpape
dc	direct current
DP	Druyvesteyn and Penning
L	Langevin
MDR	Mullaney, Dibelius, and Roehling
rf	radiofrequency
rms	root mean square

BASIC RELATIONS

Before discussing the literature in this area it is necessary to present some definitions.

For monoenergetic electrons, the collision frequency for momentum transfer $\nu_m(v)$ may be written

$$\nu_m(v) = P_m(v)p_o v = NQ_m(v)v \tag{1}$$

where $P_m(v)$ is the probability of collision for momentum transfer, p_o is the concentration of neutral particles normalized to 1 torr pressure at 273 K, v is the electron speed, N is the neutral particle concentration, and $Q_m(v)$ is the collision cross section for momentum transfer and is expressed in a variety of units, which are given in table I.

The momentum lost by an individual electron in colliding elastically with a cesium atom depends on the angle with which the electron is scattered. The collision cross section for momentum transfer is equal to the total elastic cross section only if electrons are scattered uniformly in all directions by the cesium atoms. However, the angular distribution of scattering for electrons on cesium has never been measured.

Only Brode (ref. 1) has measured the total monoenergetic cross section, which we consider to be, at low energies, the cross section for momentum transfer. Other investigators have measured the probability of collision, using electrons in some distribution of velocities usually taken to be Maxwellian. In these experiments a transport coefficient of the plasma, such as mobility or conductivity, is measured; and the collision frequency is obtained indirectly. For a plasma maintained by some mechanism other than the probing electromagnetic radiation, with electrons in a Maxwellian distribution, the effective conductivity $\langle\sigma\rangle$ has been derived by Margenau (ref. 2) from the Boltzmann equation

$$\langle\sigma\rangle = \frac{2\left(\frac{m}{2kT}\right)^{5/2}}{\Gamma\left(\frac{5}{2}\right)} \frac{ne^2}{m} \int_0^\infty \frac{v^4}{\nu_m(v) + j\omega} \exp\left(\frac{-mv^2}{2kT}\right) dv \qquad (2)$$

where m is the electron mass, e is the electron charge, T is the electron temperature, k is the Boltzmann constant, ω is the radian frequency of the probing radiation, and n is the electron concentration.

When collision frequency is not a function of velocity, equation (2) reduces to the Lorentz (ref. 3) form

$$\sigma = \frac{ne^2}{m(\nu_m + j\omega)} \qquad (3)$$

This simple form of the conductivity is used as a model for reducing measured values of conductivity to values of effective collision frequency. For example, in the direct-current limit of conductivity often employed in these measurements,

$$\sigma_{dc} = \frac{ne^2}{m\nu_m} \qquad (4)$$

and

$$\langle\sigma\rangle_{dc} = \frac{2\left(\frac{m}{2kT}\right)^{5/2}}{\Gamma\left(\frac{5}{2}\right)} \frac{ne^2}{m} \int_0^\infty \frac{v^4}{\nu_m(v)} \exp\left(\frac{-mv^2}{2kT}\right) dv \qquad (5)$$

An effective collision frequency $\langle\nu_m\rangle_{dc}$ may be defined

$$\frac{1}{\langle\nu_m\rangle_{dc}} = \frac{2\left(\frac{m}{2kT}\right)^{5/2}}{\Gamma\left(\frac{5}{2}\right)} \int_0^\infty \frac{v^4}{\nu_m(v)} \exp\left(\frac{-mv^2}{2kT}\right) dv \qquad (6)$$

Similarly, in the radiofrequency limit $\left(\omega^2 >> \nu_m^2\right)$ which applies in high-frequency measurements,

$$\langle \nu_m \rangle_{rf} = \frac{2\left(\frac{m}{2kT}\right)^{5/2}}{\Gamma\left(\frac{5}{2}\right)} \int_0^\infty \nu_m(v) v^4 \exp\left(\frac{-mv^2}{2kT}\right) dv \qquad (7)$$

Another collision frequency, the simple average collision frequency of kinetic theory $\bar{\nu}_m$ is used in the literature (ref. 4). This collision frequency is written

$$\bar{\nu}_m = \frac{2\left(\frac{m}{2kT}\right)^{3/2}}{\Gamma\left(\frac{3}{2}\right)} \int_0^\infty \nu_m(v) v^2 \exp\left(\frac{-mv^2}{2kT}\right) dv \qquad (8)$$

The differences between these four collision frequencies can be illustrated by assuming a simple relation for $\nu_m(v)$, such as

$$\nu_m(v) = Cv^l \qquad (9)$$

The resulting expressions for collision frequency would be

$$\langle \nu_m \rangle_{dc} = Cv_p^l \frac{\Gamma\left(\frac{5}{2}\right)}{\Gamma\left(\frac{5 - l}{2}\right)} \qquad (10)$$

$$\langle \nu_m \rangle_{rf} = Cv_p^l \frac{\Gamma\left(\frac{5 + l}{2}\right)}{\Gamma\left(\frac{5}{2}\right)} \qquad (11)$$

$$\bar{\nu}_m = Cv_p^l \frac{\Gamma\left(\frac{3 + l}{2}\right)}{\Gamma\left(\frac{3}{2}\right)} \qquad (12)$$

Clearly, only in the limiting case of collision frequency being independent of electron velocity ($l = 0$) do the various collision frequencies agree.

Still other definitions of collision frequency appear, based not on an unspecified relation between ν_m and v, but on the assumption that the atoms and electrons behave as hard elastic spheres on colliding. Two such expressions which have been derived on this basis and are used in the analysis of some of the data in this field are that based on Langevin (ref. 5) and on the first approximation of Chapman and Cowling (ref. 6)

$$\nu_{m,L} = \frac{4}{3} P_m p_o \langle v \rangle \tag{13}$$

where $\langle v \rangle$ is the mean speed, and that of Druyvesteyn and Penning (ref. 7)

$$\nu_{m,DP} = \frac{3}{4} \sqrt{\pi} P_m p_o v_p \tag{14}$$

Druyvesteyn and Penning also obtained equation (13) by what they described as a more accurate method. Furthermore, equation (14) is identical to equation (10) with $l = 1$, and equation (13) is identical in expression to equation (11) with $l = 1$ (although they do not apply to the same case).

Some ad hoc formulations of collision frequency appear in the literature of the cesium cross section and are mentioned here for completeness. Harris and Balfour (ref. 8) simply use the Lorentz form where collision frequency is constant. Mullaney and Dibelius (ref. 9) and Roehling (ref. 10) apparently use

$$\nu_{m,MDR} = \frac{4}{3} P_m p_o v_p \tag{15}$$

although Mullaney and Dibelius may have been using the nearly numerically equivalent relation (eq. (14)). Roehling mistakenly cites Chapman and Cowling. Finally, Bohdansky and Langpape (ref. 11) use the expression

$$\nu_{m,BL} = \frac{4}{3} P_m p_o v_{rms} \tag{16}$$

where

$$v_{rms} = \left(\frac{3kT}{m}\right)^{1/2}$$

Loeb (ref. 12) has expressed impatience with arguments revolving around the "correct" formulation to be used in reducing the data obtained in conductivity and mobility measurements, and we can only echo his sentiments. The disagreement to be found in the literature regarding the probability of collision in cesium is much greater than any of these various definitions could introduce. In fact, the experimental values of collision probabilities in the range of electron velocity from 0.35 to 0.45 $(eV)^{1/2}$ differ by a factor of 100. The foregoing discussion is included in the present summary to explain what may appear to be minor discrepancies in the data quoted in the source articles and that which has been plotted in figure 1.

MEASUREMENTS OF CROSS SECTION

Most of the data have been adjusted so that the experimental probabilities of collision plotted in figure 1 conform to equation (1). The abscissa of figure 1 is the most probable electron velocity for a Maxwellian distribution or the actual velocity of a monoenergetic beam, expressed in $(eV)^{1/2}$. Several of the papers included in this survey are already adapted to this form. Brode (ref. 1) has actually measured the monoenergetic probability of collision. Chen and Raether (ref. 13), Flavin and Meyerand (ref. 14), and Nighan (ref. 15) have reduced their effective-cross-section data to monoenergetic form by different analytical processes. The data shown for both Chen and Raether (ref. 13) and Nighan (ref. 15) include their extrapolations to electron energies somewhat beyond those actually measured in their experiments. Postma (ref. 16) has reduced the electron drift velocity data of Chanin and Steen (ref. 17) to a monoenergetic momentum transfer cross section. Nolan and Phelps (ref. 18) have reworked the data of Boeckner and Mohler (ref. 19) into this relation. Mirlin, Pikus, and Yur'ev (ref. 20) present their effective-cross-section data as if it were monoenergetic without any constant that would result from integration over a distribution. Bohdansky and Langpape (ref. 11) obtain from the data of Houston and Gibbons (ref. 21) an effective cross section which does not vary with velocity in the range of measurement. Therefore, this can be taken as the monoenergetic probability of collision and is so plotted in figure 1, using the Langevin form (eq. (13)) rather than equation (16). Ingraham (ref. 22) reduces his microwave absorption data by using the model formulated by Bers (ref. 23) and assuming ν_m is independent of velocity, although later reduction of the data indicated that ν_m is really a weak function of velocity. The probability of collision shown in figure 1 was obtained by using equation (1).

Morgulis (refs. 24 and 25); Mullaney and Dibelius (ref. 9); Golubev, Kasabov, and Konakh (ref. 26); Harris and Balfour (ref. 8); Rufeh, Kitrilakis, and Lieb (ref. 27); Hansen and Warner (ref. 28); and Harris (ref. 29) each present probability of collision data at only one electron energy using a variety of expressions for the collision frequency averaged over a Maxwellian distribution of electron velocities. Since nothing can be said about the variation of cross section with velocity when only the effective cross section at a single electron energy is reported, we have arbitrarily taken ν_m to be constant with velocity in interpreting these data. These cross sections, as plotted in figure 1, conform to the monoenergetic form (eq. (1)), which generally results in a slightly higher cross section than originally reported. However, the changes in cross section introduced by this mode of presentation are insignificant compared to the variations in results reported by different authors.

Terlouw (ref. 30) computes a direct-current conductivity averaged over a Maxwellian distribution, assuming a variation of probability of collision with velocity derived theoretically by Garrett and Mann (ref. 31). Comparing this value with his measured value of direct-current conductivity, Terlouw concludes that the probability of collision has been taken to be too high and arbitrarily divides P_m by 3, thus obtaining fair agreement with measured and calculated conductivity. His value of $P_m = 745\ cm^{-1}\ torr^{-1}$ at $v_p = 0.4$ eV is shown in figure 1.

Polushkin and Dudko (ref. 32) obtained the probability of collision from both direct-current and radiofrequency conductivity measurements in helium-cesium and argon-cesium mixtures. Electron temperature was measured by using Langmuir probes and was found to range from 3000 to 5000 K. The probability of collision, which is reported to be constant over this range of electron temperature for each of the measurements, is 708 for the direct-current experiment and 258 for the radiofrequency experiment. The direct-current results are originally presented in the Langevin form (eq. (13)) and are presented in the same way in figure 1. The radiofrequency results were presented in the form of equation (1) rather than as the averaged probability of collision (eq. (11)) with $l = 1$. This adjustment has been made in figure 1.

Both Pikus, Skvortsov, and Yur'ev (ref. 33) and Roehling (ref. 10) present collision probability data which are fairly complicated functions of electron energy, without reduction to the monoenergetic form. These data are plotted in figure 1 exactly as they appear in the original sources.

A cross section has been computed by some authors from conductivity data reported by Steinberg (ref. 34). However, Phelps (ref. 18) raises doubts as to the accuracy of the electron density measured by Steinberg, and these data have been omitted from figure 1.

Another reported cross section which has been omitted from figure 1 is that computed from data of Reichelt (ref. 35) by Wilkins and Gyftopoulos (ref. 36), who used a diode conductivity model. The values reported seem to be too scattered to contribute anything more to this survey.

The wide dispersion of experimental values of the probability of collision for momentum transfer is indicative of the difficulty of the measurement. The only direct measurement of the cesium cross section at these low electron energies was made by Brode (ref. 1), who studied the total scattering of electrons from a collimated beam in cesium vapor. The difficulty surrounding this measurement is illustrated by the fact that in nearly 40 years no one has reported results from a comparable experiment.

Most of the data on which the cross sections plotted in figure 1 are based result from measurements of the conductivity or mobility of the plasma. In most cases these are simply measurements of the current between electrodes in a heated, cesium-filled tube, with electron density and temperature measured by using a Langmuir probe. However, some variations from this procedure are noted.

Using a spectroscopic technique, Mohler (ref. 37) later supplemented the probe measurements presented in his original work with Boeckner (ref. 19) and discovered an error in the measured electron concentration. Pikus et al. (ref. 33) measured conductivity with and without a magnetic field and found considerable difference in the indicated cross section, as shown in figure 1 where the higher curve represents the cross section computed from the direct-current conductivity without magnetic field.

Harris and Balfour (ref. 8), Chen and Raether (ref. 13), Flavin and Meyerand (ref. 14), Poluskin and Dudko (ref. 32), Morgulis, Levitskiy, and Panichevskiy (ref. 25), and Ingraham (ref. 22) have used microwave techniques to measure the plasma conductivity. This method has the advantages that no net current need be conducted through the plasma, electron temperature is not disturbed by the small amounts of power absorbed by the plasma, and sheath effects can be minimized.

Mazing and Vrublevskaya (ref. 38) determined the zero energy cross section by measuring the phase shift of the absorption lines of cesium near the edge of a series. This measurement, proposed by Fermi (ref. 39) in 1934, was first used in cesium in 1938 by Fuchtbauer and Heiman (ref. 40), who found a probability of collision of 25 900. By 1966, experimental techniques had improved considerably, and Mazing and Vrublevskaya were able to make a more accurate measurement; their value for $P_m(0)$ of 5300 is plotted in figure 1.

THEORETICAL RESULTS

The theoretical calculations of the electron-cesium probability of collision, plotted in figure 2 show little agreement with each other or with most of the experimentally determined cross sections of figure 1. All authors cited in figure 2 present their results in the form of monoenergetic total elastic collision probability. However, Karule (ref. 41), Crown and Russek (ref. 42), and Stone and Reitz (ref. 43) have also expressed their results in the form of the monoenergetic probability of collision for momentum transfer, as shown in figure 2. Garrett and Mann (ref. 31) produce only the total elastic collision probability. Robinson (ref. 44) does compute an effective cross section for momentum transfer, but we have chosen to present his monoenergetic total elastic cross section in figure 2.

Due to the remarkable lack of agreement among the measured cross sections, there is no entirely satisfactory means of evaluating the various theoretical results. However, each succeeding author in this field has discussed the work of his predecessors in critical terms, pointing out how one mathematical model or computational technique is more valid or accurate than another.

Karule (ref. 41) demonstrates that the adiabatic approximation used by some tends to overestimate the cross section, compared to the results from his close-coupling exchange approximation.

Crown and Russek (ref. 42) calculated the cross section by using the adiabatic approximation including exchange. They criticize Robinson (ref. 44) and Garrett and Mann (ref. 31) for using a phenomenological potential function, inaccurate at small separations, to describe the interaction between the electron and the scattering atom; they also question the polarizability calculated by Stone and Reitz (ref. 43). In addition, Crown and Russek suggest that such computational matters as the convergence criteria and increment of integration are not sufficiently refined in these earlier works.

Stone and Reitz (ref. 43), who introduced the adiabatic model including exchange, point out three defects in Robinson's calculation: a lack of self-consistent wave functions, no accounting for the effect of exchange, and the arbitrarily chosen potential function also criticized by Crown and Russek.

Salmona and Seaton (ref. 45), have computed a total cross section for cesium, but it is omitted from figure 2 since it is for the range of electron energies from 4 to 100 eV.

CONCLUSIONS

The experimental results differ from each other not only in the magnitude of the cross section at various electron energies, but also in the shape of the plots. Mazing and Vrublevskaya (ref. 38), Chen and Raether (ref. 13), Ingraham (ref. 22), Postma (ref. 16), Boeckner and Mohler (refs. 18, 19, and 37), and Nighan (ref. 15) all indicate that the probability of collision increases as the electron energy approaches zero, which agrees qualitatively with most of the theoretical results. However, Roehling (ref. 10), Flavin and Meyerand (ref. 14), and Pikus, Skvortsov, and Yur'ev (ref. 33) show a cross section that is decreasing as it approaches zero electron energy. Further, Brode (ref. 1) shows a pronounced dip in the probability of collision near 1 eV, where Nighan's results (ref. 15) indicate a large maximum. In the range between 0.5 and 0.6 $(eV)^{1/2}$, Polushkin reports a constant cross section, while Nighan found a broad minimum and

Postma a pronounced peak. No one else observes the almost discontinuous rise in cross section near 0.4 $(eV)^{1/2}$ reported by Pikus et al.

As for the theoretical papers, the more recent calculations may indeed be more accurate, but the only true test of this accuracy would lie in a favorable comparison to experimental results. This test is not now feasible, considering the lack of agreement among experimentally determined probabilities of collision.

An effort has been made to assemble a comprehensive collection of all the measured and calculated values of the electron-cesium atom probability of collision for momentum transfer. However, the result of this effort, shown in figures 1 and 2, gives eloquent testimony to the need for much careful work on this subject, but offers little assistance to the worker who must make an estimate of the collision frequency at the present time. Only time and further experimentation will unravel the correct probability of collision. In the meantime, this survey would not be of practical value without recommending, or at least calling attention to, some results which are more likely to be correct than others.

At zero energy, the cross section found by Mazing and Vrublevskaya, who carefully used an accurate spectroscopic technique, must be regarded as the best value now known. This would tend to refute results which show a decrease in cross section at low energies. At the high end of the energy range considered, the work of Brode, even after 40 years, must still be respected, if for no other reason than the classical directness of his approach.

In the range of energy between these extremes, which happens to be the range of greatest interest for many electronics applications as well as the range which contains the greatest reported variations, the correct results are less easily chosen. For electron energies just below those in Brode's data, the bulk of the values reported indicate that the probability of collision drops at least a little. The exceptions to this are Postma, and Boeckner and Mohler, as corrected by Phelps. There seems to be no accounting for the high peak calculated by Postma from Chanin's data; Nighan estimates that Boeckner and Mohler's cross section is too high because of failure to completely account for electron-ion interactions. For the range from 0.5 to 0.7 $(eV)^{1/2}$, all other reports indicate a cross section lower than Brode's and one which is constant, or nearly constant, with electron velocity.

The data which most successfully bridge the gap between the region around 0.6 $(eV)^{1/2}$ and Mazing and Vrublevskaya appear to be those of Ingraham. These data were obtained by using a microwave measurement technique which disturbs the plasma negligibly. The electron density was low enough that electron-ion effects are also negligible. The data were taken in the afterglow of a pulsed discharge at a time sufficient for the electron gas to have randomized. Furthermore, the shape of the absorption curves supports the assumption of a Maxwellian distribution. The monoenergetic cross section deduced by Chen and Raether from their microwave data, also taken in the late afterglow of a pulsed discharge, rises more rapidly with decreasing velocity than that of Ingraham. However, it is difficult to compare the two since Ingraham's results have been only approximately reduced to the monoenergetic form.

If a set of values must be recommended, they would be, in order of increasing electron velocity, those of Mazing and Vrublevskaya, Ingraham, and Brode. In the range between Ingraham and Brode, the probability of collision probably falls to some broad minimum. Such a drop in collision probability near 0.6 $(eV)^{1/2}$ contradicts the rising trend in the Brode data below 1 eV, but agrees with that of the majority of other researchers, including the isolated point measured by Ingraham at 0.77 $(eV)^{1/2}$.

The general lack of replication found in the literature must certainly promote skepticism regarding any recommendations of the probability of collision, including those made here. The obvious conclusion which arises from this survey is that further work, especially replication of experiment, is needed to establish the correct value of this important physical quantity.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 15, 1969,
129-02.

REFERENCES

1. Brode, Robert B.: The Absorption Coefficient for Slow Electrons in Alkali Metal Vapors. Phys. Rev., vol. 34, no. 5, Sept. 1, 1929, pp. 673-678.
2. Margenau, H.: Conduction and Dispersion of Ionized Gases at High Frequencies. Phys. Rev., vol. 69, no. 9-10, May 1-15, 1946, pp. 508-513.
3. Lorentz, Hendrik A.: The Theory of Electrons and Its Applications to the Phenomena of Light and Radiant Heat. Second ed., Dover Publ., 1952.
4. Present, Richard D.: Kinetic Theory of Gases. McGraw-Hill Book Co., Inc., 1958.
5. Langevin, P.: Une Formule Fondamentale de Théorie Cinétique. Ann. de Chimie et de Physique, Ser. 8, vol. 5, pp. 245-288, 1905. (Translation appears in E. W. Mc Daniel: Collision Phenomena in Ionized Gases. John Wiley & Sons, Inc., 1964, pp. 701-726.)
6. Chapman, Sydney; and Cowling, T. G.: The Mathematical Theory of Non-uniform Gases. Second ed., Cambridge, University Press, 1952.

7. Druyvesteyn, M. J.; and Penning, F. M.: The Mechanism of Electrical Discharges in Gases of Low Pressure. Rev. Mod. Phys., vol. 12, no. 2, Apr. 1940, pp. 87-174.

8. Harris, J. H.; and Balfour, D.: Microwave Cavity Studies of Ionization Decay in Caesium Vapour. Brit. J. Appl. Phys. ser. 2, vol. 1, no. 4, Apr. 1968, pp. 409-423.

9. Mullaney, George J.; and Dibelius, Norman R.: Determination of Electron Density and Mobility in Slightly Ionized Cesium. ARS J., vol. 31, no. 11, Nov. 1961, pp. 1575-1576.

10. Roehling, Duane: The Electrical Resistivity of a Partially Ionized Cesium Plasma. Adv. Energy Conversion, vol. 3, no. 1, Jan.-Mar. 1963, pp. 69-76.

11. Bohdansky, J.; and Langpape, R.: Analysis of the I-V (Current-Voltage) Curve of a High-Pressure Cs Diode. Sixth Compt. Rend. Conf. Intern. Phenomenes Ionisation Gaz. Vol. 4, 1963, pp. 543-545.

12. Loeb, Leonard B.: Basic Processes of Gaseous Electronics. Second ed., University of California Press, 1955, p. 220.

13. Chen, C. L.; and Raether, M.: Collision Cross Section of Slow Electrons and Ions with Cesium Atoms. Phys. Rev., vol. 128, no. 6, Dec. 15, 1962, pp. 2679-2683.

14. Flavin, Richard K.; and Meyerand, Russell G., Jr.: Collision Cross Section of Low Energy Electrons with Cesium Atoms. Thermionic Conversion Specialist Conference. IEEE, 1963, pp. 10-16.

15. Nighan, William L.: Low-Energy Electron Momentum Transfer Collisions in Cesium Plasmas. Phys. Fluids, vol. 10, no. 5, May 1967, pp. 1085-1094.

16. Postma, A. J.: Calculation of the Momentum Transfer Cross Section of Electron-Atom Collisions in Cesium Vapour from Drift Velocity Measurements. Phys. Letters, vol. 26A, no. 10, Apr. 8, 1968, pp. 492-493.

17. Chanin, Lorne M.; and Steen, R. D.: Drift Velocities in Cesium. Phys. Rev., vol. 136A, no. 1, Oct. 5, 1964, pp. 138-141.

18. Nolan, J. F.; and Phelps, A. V.: Measurement of Cesium Excitation Cross Section near Threshold by a Swarm Technique. Phys. Rev., vol. 140A, no. 3, Nov. 1, 1965, pp. 792-799.

19. Boeckner, C.; and Mohler, F. L.: Scattering of Electrons by Ions and the Mobility of Electrons in a Cesium Discharge. Nat. Bur. Standards J. Res., vol. 10, 1933, pp. 357-363.

20. Mirlin, D. N.; Pikus, G. E.; and Yur'ev, V. G.: Determination of Electron Scattering Cross Section by the Electrical Conductivity of Weakly Ionized Gas. Soviet Phys. Tech. Phys., vol. 7, no. 6, Dec. 1962, pp. 559-561.

21. Houston, J. M.; and Gibbons, M. D.: Cesium Ion Neutralization of Thermionic Converters. MIT Physical Electronics Conference, 1961, pp. 106-115.

22. Ingraham, J. C.: Electron-Atom Collision Cross-Section Measurements in the Afterglow of a Pulsed Cesium Plasma. Proceedings of the 7th International Conference on Phenomena in Ionized Gases. Vol. 1. B. Perović and D. Tošić, eds., Gractevinska Knjiga Publ. House, Belgrade, 1966, pp. 57-60.

23. Allis, William P.; Buchsbaum, Solomon J.; and Bers, Abraham: Waves in Anisotropic Plasmas. MIT Press, 1963.

24. Morgulis, N. D.; and Korchevoi, Yu. P.: Mobility and Scattering Cross Section of Electrons in Weakly Ionized Cesium Plasma. Soviet Phys. Tech. Phys., vol. 7, no. 7, Jan. 1967, pp. 655-656.

25. Morgulis, N. D.; Levitskiy, S. M.; and Panichevskiy, V. A.: Determination of Caesium Gas Discharge Plasma Parameters by Microwave Method. NASA TT F-8980, 1964.

26. Golubev, V. S.; Kasabov, G. A.; and Konakh, V. F.: Study of a Steady-State Argon-Cesium Plasma with Nonequilibrium Conductivity. High Tem., vol. 2, no. 4, July-Aug. 1964, pp. 445-459.

27. Rufeh, F.; Kitrilakis, S. S.; and Lieb, D.: The Effect of Electron Scattering on Collector Work Function Measurement. Thermionic Conversion Specialist Conference, IEEE, 1965, pp. 147-155.

28. Hansen, Lorin K.; and Warner, Charles: The Electron-Rich, Unignited Mode of Thermionic Converters. Thermionic Conversion Specialist Conference. IEEE, 1963, pp. 44-50.

29. Harris, Lawson P.: Electrical Conductivity of Cesium-Seeded Atmospheric Pressure Plasmas near Thermal Equilibrium. J. Appl. Phys., vol. 34, no. 10, Oct. 1963, pp. 2958-2965.

30. Terlouw, J. C.: Experimental Study of a Highly Ionized Steady-State Cesium Plasma. Rijnhuizen Report 64-15, Associatie Euratom- FOM, FOM-Instituut Voor Plasma-Fysica, Rijnhuizen, Jutphaas, Nederland, 1964.

31. Garrett, W. R.; and Mann, R. A.: Model for the Scattering of Slow Electrons by Cesium Atoms. Phys. Rev., vol. 130, no. 2, Apr. 15, 1963, pp. 658-660.

32. Polushkin, I. N.; and Dudko, D. Y.: Effective Outline of Electron Scattering in Plasma, in Helium, and in Argon with a Mixture of Cesium Vapor. Rep. FTD-HT-23-919-67, Air Force Systems Command, Oct. 6, 1967, (Available from DDC as AD-674224.)

33. Pikus, G. E.; Skvortsov, N. S.; and Yur'ev, V. G.: Measurement of Electron Mobility According to the Variation of Plasma Resistance in a Magnetic Field. Soviet Phys. JETP, vol. 15, no. 2, Aug. 1962. pp. 225-230.

34. Steinberg, Richard K.: Hot-Cathode Arcs in Cesium Vapor. J. Appl. Phys, vol. 21, no. 10, Oct. 1950, pp. 1028-1035.

35. Reichelt, Walter H.: Spectrographic Investigation of the Ignited Mode of Thermionic Converter Operation. European Nuclear Energy Agency and Inst. Elect. Eng. International Conference on Thermionic Electrical Power Generation, London, Eng., Sept. 20-25, 1965.

36. Wilkins, Daniel R.; and Gyftopoulos, Elias P.: Thermionic Converters Operating in the Ignited Mode, Part II. Thermionic Conversion Specialist Conference, IEEE, 1965, pp. 53-64.

37. Mohler, Fred L.: Electron Concentration and Spectral Intensity Distribution in a Cesium Discharge. J. Res., Nat. Bureau Standards, vol. 17, Dec. 1936, pp. 849-857.

38. Mazing, M. A.; and Vrublevskaya, N. A.: Spectroscopic Investigation of the Elastic Scattering of Slow Electrons by Cesium and Argon Atoms. Soviet Phys.-JETP, vol. 23, no. 2, Aug. 1966, pp. 228-231.

39. Fermi, Enrico: The Displacement by Pressure of the High Terms of Spectral Series. Nuovo Cimento, vol. 11, 1934, pp. 157-166.

40. Füchtbauer, Chr.; and Hermann, Gg.: Über Verbreiterung und Verschiebung der Höheren Serienlinien des Natriums durch Cesiumdampf. Jeit. f. Physik, vol. 110, no. 1-2, Aug. 2, 1938, pp. 8-20.

41. Karule, E.: Elastic Scattering of Low-Energy Electrons by Alkali Atoms. Proceedings of the IVth International Conference on the Physics of Electronic and Atomic Collision. Science Bookcrafters, Inc., 1965, pp. 139-143.

42. Crown, J. C.; and Russek, A.: Electron-Alkali-Atom Interaction Potential and Elastic-Scattering Cross Section. Phys. Rev., vol. 138A, no. 3, May 3, 1965, pp. 669-682.

43. Stone, Philip M.; and Reitz, John R.: Elastic Scattering of Slow Electrons by Cesium Atoms. Phys. Rev., vol. 131, no. 5, Sept. 1, 1963, pp. 2101-2107.

44. Robinson, Lawrence B.: Theoretical Elastic Collision Frequency between Electrons and Neutral Atoms in a Cesium Plasma. Phys. Rev., vol. 127, no. 6, Sept. 15, 1962, pp. 2076-2080.

45. Salmona, A.; and Seaton, M. J.: Electron Collisions with Na Atoms. Proc. Phys. Soc. (London), vol. 77, pt. 3, Mar. 1961, pp. 617-629.

TABLE I. - USEFUL CONVERSION FACTORS

$P_m(v)\ (\text{torr cm})^{-1} = 0.989\ Q_m(v)\ \left(a_o^2\right)$
$P_m(v)\ (\text{torr cm})^{-1} = 3.12\ Q_m(v)\ \left(\pi a_o^2\right)$
$P_m(v)\ (\text{torr cm})^{-1} = 3.54\times10^{16}\ Q_m(v)\ (\text{cm}^2)$
$P_m(v)\ (\text{torr cm})^{-1} = 3.54\times10^{20}\ Q_m(v)\ (\text{m}^2)$
1 Rydberg = 13.605 eV
1 atomic unit = 27.21 eV
$p_o = p\ \frac{T}{273\ K}$

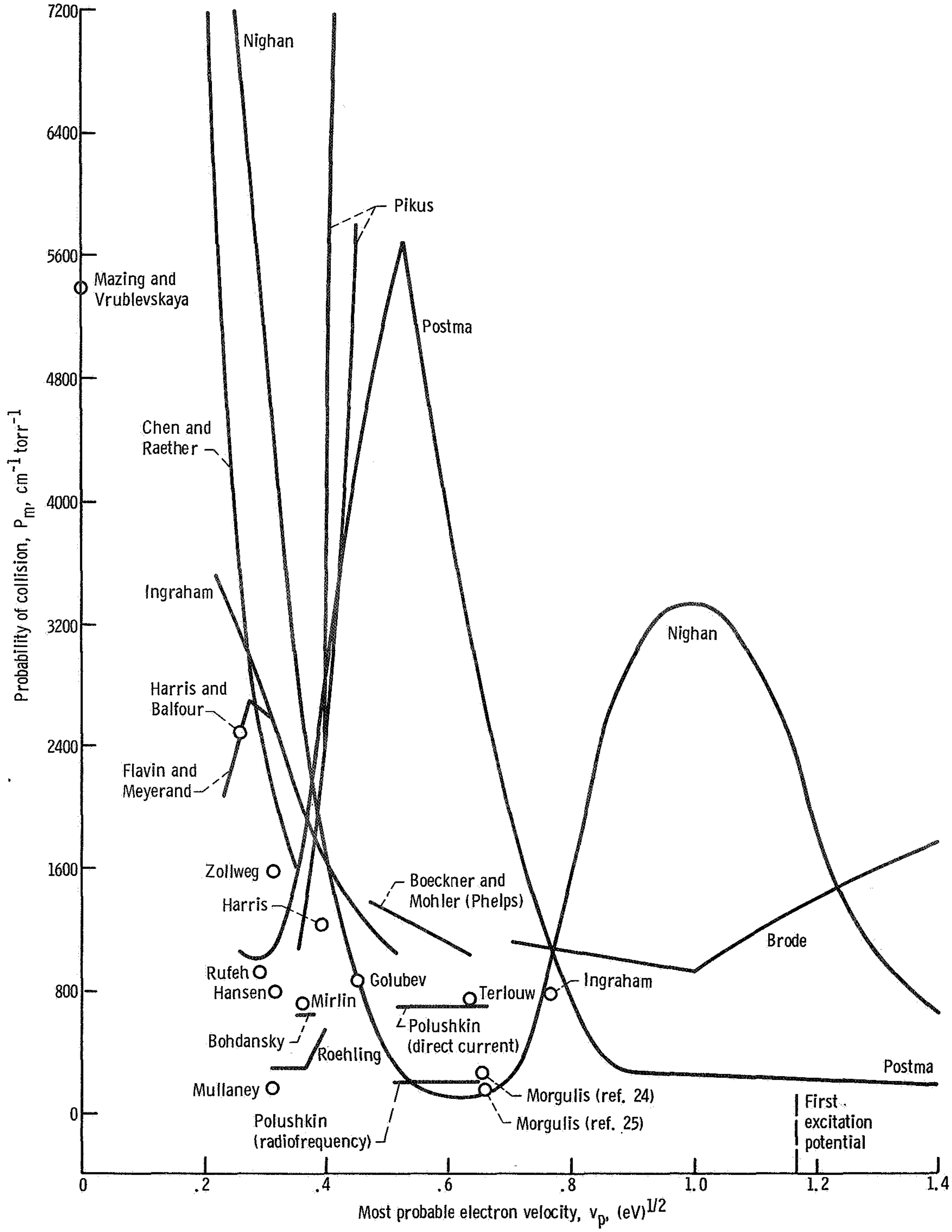

Figure 1. - Experimental probability of collision.

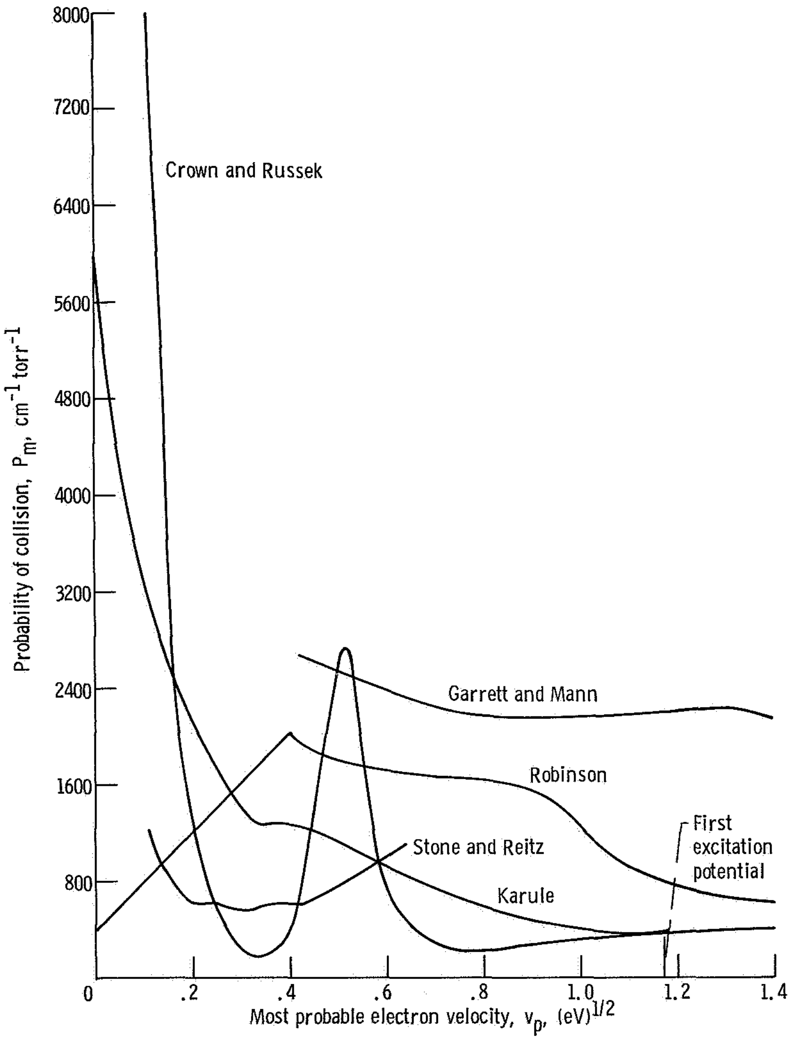

Figure 2. - Theoretical probability of collision.

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